IN QUEST OF THE QUANTUM

Mir Publishers

Moscow

L. Ponomarev

In Quest of the Quantum

by Leonid Ponomarev

Translated from the Russian
by Nicholas Weinstein

Mir Publishers
Moscow

UDC 530.1: 20

First published 1973
Revised from the 1971
Russian edition

На английском языке

$\text{П}\frac{0232-240}{041(01)-73}$

FROM THE AUTHOR

A current opinion has it that it is too early to acquaint beginners in science with certain of its facts, and embarrassing to try to explain these facts to persons versed in the art. This is most often referred to when an attempt is made to describe the structure of the atom. This perhaps is why no book has yet been written on quantum mechanics, sufficiently strict to offer no offence to the expert, sufficiently simple not to frighten away the novice and, at the same time, interesting to both.

This book is not for professionals, though they also may find some things here that might seem surprising to them. It is for those who are finishing school and for those who try to take a broader view of this best of all worlds than they have been trained to do in their profession which must of necessity be narrow if it is to be productive.

The history of the atom is related quite rigorously in the book you have before you. But this strictness is no end in itself. As a rule, not only the facts as such are of interest, but their interpretation as well, and the circumstances in which they were discovered. Therefore, as a stem, I have taken the evolution of the ideas and concepts of atomic physics, showing that they constitute a united system of simple and harmonic design. It was in fact this intrinsic beauty of quantum theory that incited me to write this book. I shall consider my efforts worthwhile if the reader understands the power of the logical constructions of quantum mechanics and perceives the perfection of their unforeseeably simple consequences.

Contents

Facts

Part One

Chapter One

ATOMS * RAYS * QUANTA

Not many people can intelligently answer the question: what is quantum mechanics? The rest are simply convinced that it is a very difficult science. This is very likely untrue, but the certainty with which this opinion has taken root is not without reasons. Essentially, the logic of quantum mechanics is simple enough. Nevertheless, to become accustomed to it we must first master several concepts which seem in no way to be related to one another. These concepts form no orderly system at first, but only after lengthy rearrangement and meditation.

This requires much time and effort.

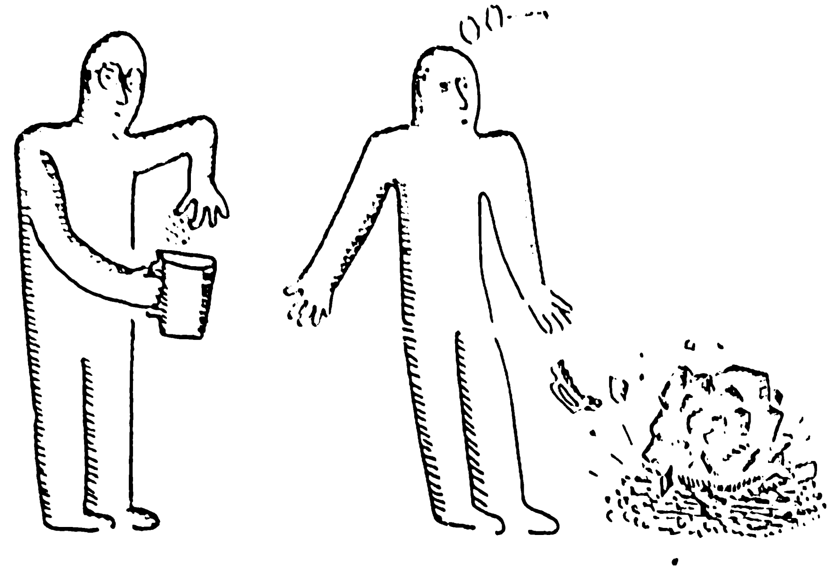
If all you know about quantum mechanics is that it has "solved the age-old riddle of the mysterious microcosm" and that it has "overturned all our conceptions of the universe", you know no more than tourists do about an unfamiliar country through which they travel without having first learned something about its culture and language. They see people about them, hurrying, laughing and waving their hands, but understand neither where they are going nor the cause

of their gaiety. As a result, the memory of the travellers retains only gaily coloured signboards in an unknown language.

Quantum mechanics is a vast country with a rich and profound culture. However, to understand its culture we must first learn its language. This language is peculiar but does not, in essence, differ from any other foreign language. As any language, it cannot be mastered by will-power alone; some kind of system is required. You can begin by simply memorizing several common conceptions and by trying to arrange them into elementary sentences without taking too much trouble over the strictness of their grammatical construction. Only long afterwards do you acquire the ease and confidence that comes with the mastery of a new language and which are accompanied by a feeling of satisfaction and the joy of pure knowledge.

Most people probably learn quantum mechanics in a way that resembles the dissolving of salt in water. At first, fine grains of salt poured into a glass of water disappear without leaving even a trace. This continues until finally there comes a moment when the addition of just one more grain is sufficient to initiate the gradual growth of a large regular crystal in the solution.

In this book we will trace back the sources, ideas and discoveries of quantum mechanics, explain its system of concepts and views and, finally, its applications. But first we must dissolve several grains of the initial concepts and master the several necessary words without which it is impossible to construct a single intelligent "quantum sentence". Sometimes this turns out to be wearisome work. Nobody, however, can make a space flight without first running, jumping, and whirling in a centrifugal simulator, all of which can hardly be described as particularly romantic. The famous Russian physiologist Ivan Mikhailovich Se-



chenov liked to repeat the maxim that "to develop a muscle, you must tire it". Forbid yourself, once and for all, to experience fatigue and you will never perceive the thrill of exciting research, the joy of discovery and that unselfish interest for trivial details that has created, essentially, not only quantum mechanics, but all of science.

All this has been said not to overawe the reader with unsurmountable obstacles at the very beginning of his journey through the foreign land of the quantum. But judge for yourself: no knowledge pills have yet been concocted that would enable you to wake up in the morning a full professor of physics. So let us begin by mastering three ideas: *atoms*, *rays* and *quanta*. They underlie all atomic physics.

ATOMS

What then is quantum mechanics? *Quantum mechanics is the science of the structure and properties of atomic objects and phenomena.*

Everything is correct in this definition, and yet it will be useless unless we explain the concepts it is made up of. Indeed, what, for instance, do the words "properties of atomic objects", i. e. atoms, mean?

No such question arises if, for example, we are referring to a ripe watermelon. Its properties can be fully determined by our five senses: it is round (or oblong), heavy, juicy, smells fresh and splits with a crackle when we cut it open. But what can we do about atoms (of which, by the way, our watermelon consists)? They can be neither seen nor touched directly. This does not mean, of course, that no such things exist. It merely indicates that the properties of atoms are entirely different from those of a whole watermelon.

There are few people nowadays for whom the reality of atoms is less evident than the motion of the earth around the sun. To almost everybody the concept of the atom is associated with the intuitive notion of something extremely minute and indivisible. But what, then, is the meaning given by modern physics to the concept of the atom? How did this concept appear, what was understood by it in ancient times, how did it subsequently develop and why could only quantum mechanics fill this speculative scheme with a real content?

The idea of the atom is usually considered to have been first proposed by the ancient Greek philosopher Democritus, though history also mentions his teacher Leucippus of Miletus (or perhaps Elea) and, with less certitude, the ancient Hindu philosopher Kanada who lived just before the beginning of the Christian Era and was one of the early atomists (his name in the Sanskrit means "devourer of atoms"). According to Kanada (otherwise Kanabhuj or Kanablaksha), the infinite divisibility of matter is absurd because "... the infinite is always equal to the infinite". The tiniest particle in nature, taught Kanada, is a speck of dust in a sunbeam. It consists of six atoms linked pairwise "by the will of God or for some other good reason".

Our knowledge about Democritus is very scarce.

We know that he was born in the Ionian colony of Abdera on the Thracian shore of the Mediterranean; that he was a disciple of Leucippus and, in addition, was taught by the Chaldeans and the Persian Magi; that he travelled much and knew much; that he lived about a hundred years and was given a public burial about 370 B.C. by the citizens of his native Abdera, who held him in great esteem. Later generations of artists always depicted Democritus as a tall man with a short beard, wearing a white tunic and sandals on his bare feet.

Legend has it that Democritus once sat on a stone by the seashore, held an apple in his hand and reasoned: "If I cut this apple in half I will have two halves, if I cut one half in two I will have two fourths. Now if I continue to divide the remaining parts in the same way, will I continue to obtain an eighth, a sixteenth, a thirty-second, etc. of an *apple*? Or will a time come when the divided parts will no longer possess the properties of an apple?" It turned out subsequently that Democritus' doubt (as do almost all unselfish doubts) contained a grain of truth. On second thought, the philosopher came to the conclusion that a limit to such divisibility exists. He named the last, already indivisible, particle an *atom* (from the Greek *atomos* meaning indivisible). He set down his views in a book called the *Little World System*. Though none of his writings survived, remarks about his teaching can be found in the works of other philosophers, most of whom did not agree with Democritus. The following are fragments of what he wrote more than two thousand years ago.

"The universe is made up, in reality, of nothing but atoms and the void; all the rest exists only in the mind. There are countless worlds and each has a beginning and an end in time. And nothing is ever be-

gotten of nothing, nor can it be destroyed and returned to nothing. And the atoms are innumerable in size and quantity, moving in all directions in a void, colliding and forming vortices in which all complex substances arise: fire, water, air and earth. The fact is that these, in essence, are but combinations of certain atoms. Atoms are indestructible and unchangeable owing to their hardness."

Democritus could not prove these statements; he proposed that his word be taken for it. They were not accepted, however, by other philosophers and primarily by his great contemporary Aristotle. When Democritus died, Aristotle, the future teacher of Alexander the Great, was only fourteen years old. In his prime, Aristotle was thin, not very tall and extremely elegant. He was held in universal esteem that knew no sensible bounds. There were good reasons for this; he had mastered all the knowledge extent in that age.

Aristotle was opposed to the idea of atomism: he held that an apple can be divided into smaller and smaller pieces infinitely, at least in principle. This became the prevailing view. Democritus was forgotten for many centuries, and his works were painstakingly destroyed with a fervour worthy of a better cause. This is why his teachings have come down to us only in fragments and attestations of his contemporaries. Democritus and his works became known in Europe from the poem called *De Rerum Natura* ("On the Nature of Things") by Titus Lucretius Carus (c. 95-55 B.C.).

It is senseless to blame the ancients for preferring Aristotle to Democritus; for them both systems were equally reasonable and acceptable. The aim of their science was not in its practical application (which embarrassed them). They hoped to reach by specula-

tion that feeling of harmony of the world that one obtains from any rounded-out philosophy.

It took two thousand years to overcome the erroneous views of this greatest of Greek philosophers. Physics as a science came into existence in the 17th century and it soon supplanted ancient natural philosophy. The new science was based on experiments and mathematics rather than on pure speculation. People began to *study* nature around them instead of merely *observing* it; they began to conduct deliberate experiments to check various hypotheses, and to record the results of these tests in the form of numbers. Aristotle's idea could not pass such a test. Democritus' hypothesis could, though, as we shall see further on, almost nothing has remained of its initial substance.

After twenty centuries of oblivion, the idea of atoms was restored to life by the French philosopher and teacher, Pierre Gassendi (1592-1655), for which he was persecuted by the church. During the Middle Ages, scientists were not only persecuted for various hypotheses, but also for rigorous facts if these facts contradicted universally recognized dogmata. Nevertheless, the atomistic hypothesis was accepted by all the most advanced scientists of the time. Even Newton, with his famous motto *Hypotheses non fingo* ("I frame no hypotheses"), believed in it and expounded it in his own way at the end of the third volume of his *Opticks*.

However, notwithstanding its attractiveness, the hypothesis unverified by experiments was doomed to remain only a hypothesis.

The first clear proof that Democritus was right, rather than Aristotle, was found by the Scottish botanist Robert Brown (1773-1858). In 1827, he was the quiet middle-aged keeper of the Banksian depart-

ment (later the department of botany) at the British Museum. In his youth he spent some years travelling with an expedition in Australia and brought back about four thousand species of plants. Twenty years later, he was still studying the collections. In the summer of 1827, Brown observed that the finest pollen grains of the plant *Clarkia pulchella* have an irregular motion when suspended in water due to the actions of some unknown force. He soon wrote and published a paper on this matter; its title was typical of that unhurried age: "A Brief Account of Microscopical Observations Made in the Months of June, July and August, 1827, on the Particles Contained in the Pollen of Plants; and on the General Existence of Active Molecules in Organic and Inorganic Bodies."

At first his experiment gave rise to perplexity, which was worsened by Brown himself when he tried to explain the phenomenon as the result of some "vital force" inherent in all organic molecules. Naturally, such an artless explanation of the Brownian motion could not satisfy scientists, and they continued their investigations. Especially persistent were the Belgian Father Ignace Carbonnelle (1880) and the Frenchman Louis Georges Gouy (1888). They conducted careful experiments and found that Brownian motion did not depend upon such external influences as the time of the year or day, the addition of salts, the kind of pollen used, and "is observed equally well at night on a subsoil in the country as during the day near a populous street where heavy vehicles pass. It does not depend even upon the type of particles but only on their size and, what is most important, it never ceases". (Nineteen centuries before Brown these properties of the Brownian motion were first pictured by the imagination of Lucretius and described in detail in his famous poem.)

This strange motion did not initially attract the attention it deserved. Most physicists had heard nothing about it, and those who had considered it to be devoid of interest because they held it to be similar to the motion of specks of dust in a sunbeam. It took about forty years, probably, for the idea to take shape that the random motions of plant pollen seen in a microscope were due to chance impacts of tiny invisible particles of the liquid in which the pollen grains were suspended. Almost everybody was convinced of this when Gouy's work was published, and the atomic hypothesis acquired numerous supporters.

Many people were quite sure, even before Brown's time, that all bodies are built up of atoms. Certain properties of atoms were obvious to them without any further investigations. Notwithstanding the enormous differences found among them, all bodies in nature have weight and size. Evidently, their atoms must also have weight and size. Precisely these properties of atoms formed the basis for the reasoning of John Dalton (1766-1844), an unassuming teacher of mathematics and natural philosophy at New College in Manchester and a great scientist who determined the development of chemistry for approximately the next hundred years.

One question that immediately arose before converts to atomism was: does the great diversity of bodies signify as great a diversity of atoms as maintained by Democritus? This proved to be wrong. John Dalton, after investigating chemical reactions in detail, first clearly formulated in 1808 the definition of a chemical element: *an element is a substance that consists of atoms of a single kind.*

Chemists found that elements were not so numerous; about 40 were known at that time (we know of 104 now). All other substances are made up of molecules

which are various combinations of atoms. The atoms of the elements themselves also differ from one another. One such difference was soon discovered; it turned out to be the mass of the atom. By setting the atomic weight of the lightest gas—hydrogen—arbitrarily equal to 1, it became possible to express the atomic weights in terms of this basic unit. In these units the atomic weight of oxygen equals 16, that of iron 56, etc. Thus, numbers were first made use of in the science of the atom. This was an event of extraordinary importance.

As before, however, nothing was known of the absolute sizes and masses of atoms.

One of the very first scientific attempts to evaluate the size of atoms was made by Mikhail Vasilyevich Lomonosov (1711-1765). In 1742, he noted that in making gold leaf the most skillful jewellers could beat gold into sheets one ten-thousandth of a centimetre thick (10^{-4} cm). Consequently, an atom of gold could not be larger in size. In 1773, Benjamin Franklin (1706-1790) noted that a teaspoonful of oil (about 4 cm^3 in volume), poured on the surface of still water of a lake, spreads out over an area of 0.2 hectare (about 0.5 acre, or 2000 square metres, or $2\times10^7 cm^2$). Evidently, the diameter of a molecule in this case cannot exceed $d=\frac{4\ cm^3}{2\times10^7\ cm^2}=2\times10^{-7}$ cm (i.e. two ten-millionths of a centimetre).

The work of a physics teacher of the Vienna University Joseph Loschmidt (1821-1895) should be considered the first really successful endeavour to determine the size and mass of atoms. In 1865, he found that the size of all atoms is approximately the same and is equal to 10^{-8} cm, and that an atom of hydrogen weighs only 10^{-24} grams.

This is the first time we have dealt with such minute

quantities here, and we just don't possess the necessary experience to comprehend them. The most we can do is to say "light as down" or "as thin as a cobweb". Although one ounce of cobweb is sufficient to be stretched across the Atlantic, it is still something that can be weighed and quite real. But the thickness of a cobweb exceeds the diameter of atoms by a million times and a down pillow is something of appreciable weight and quite tangible. Comparisons are usually resorted to when we wish to bridge the gap between common sense and the smallness of these numbers.

Let us take an atom of the watermelon mentioned at the beginning of our account and a cherry one centimetre in diameter, and increase them simultaneously in size. When the cherry reaches the size of the earth, the atom of the watermelon will just begin to resemble, in both weight and size, a good ripe watermelon.

Such comparisons are evidently not of great value because the concept of size as a quantity measured by applying a scale loses its initial meaning for objects that are so small. Hence, it is better from the very beginning to abandon all efforts to picture such numbers. Notwithstanding their extraordinary smallness, these numbers are not arbitrary. It is important to understand that exactly such small diameters and masses must be attributed to atoms for the properties of the matter of which these atoms consist to be as we observe them in nature.

Loschmidt obtained these values by studying the mutual diffusion of gases, that is their capacity for intermixing when brought into contact with each other. (This phenomenon is well known though it is only brought home to us when we are suddenly confronted with the smell of freshly mown hay.) Loschmidt made use of the *molecular-kinetic hypothesis*, which is the assumption that gases do not consist simply of mole-

cules, but of *travelling molecules*. By applying formulas based on the kinetic theory of gases, he also determined the mean distance between the molecules of a gas. He found it to be approximately ten times the diameter of the atoms.

If a gas is converted into a liquid, its volume is reduced to about one-thousandth of what it was before. This means that the distance between the atoms is only one-tenth of what it was. Consequently, the atoms in a liquid or solid body are pressed tightly against one another. They do not, however, cease to move; only their motion is constrained and obeys other laws than those of the motion of molecules in a gas.

The number of molecules in 1 cm^3 of a gas at normal atmospheric pressure and the temperature of melting ice

$$L = 2.688408 \times 10^{19}\ 1/\text{cm}^3$$

is now known with great precision and is called Loschmidt's number. It is approximately tenfold the value initially obtained by Loschmidt.

RAYS

Iron consists of atoms as does any other substance. If one end of an iron poker is pushed into a furnace it will get hot. From the point of view of kinetic theory this means that the atoms of iron begin to move faster (this can be detected by touching the other end of the poker with the fingers). Hence, heat is the energy of moving atoms. But this is not all that happens.

In heating the poker we observe an amazing phenomenon: with a rise in the temperature of the furnace, the *colour* of the heated iron gradually changes from a dull cherry-red to a dazzling white. Now, we cannot touch the hot poker any longer, we cannot even bring

our hand close to it. This last is incomprehensible if we make use only of the conception of the motion of atoms. We did not touch the poker; the atoms of iron did not strike our hand. Why then do we feel the heat?

Here, for the first time, we are confronted with a situation that we warned about at the very beginning. We will have to introduce a new conception which, at first glance, has nothing to do with the idea of atoms. This is *radiation.*

We say that the sun's rays light up the glade. Hence, light is a form of radiation. But we also say that we warm ourselves in the sun's rays. Consequently, heat also propagates in the form of rays. On the whole, we are concerned with radiation all the time: when we sit at a bonfire, feast our eyes upon a splendorous sunset, turn the knobs of a radio set or have an X ray made of our chest. All kinds of radiation: heat, light, radio waves and X rays, are manifestations of *the same electromagnetic radiation.* We do not, however, distinguish between the different kinds of radiation only qualitatively and subjectively, we differentiate between them strictly quantitatively as well. By what feature? Electromagnetic radiation has many features but, for the present, we are interested in only one: its wave nature.

There are probably a thousand and one textbooks in which the properties of waves are dealt with better and in more detail than we shall. You will, however, be reminded of them for the same reason that even profound academic encyclopaedias list some quite understandable everyday words.

"Wave" is one of the most vital words in physics.

Each person pictures waves differently: one sees the waves originated when a stone is thrown into a pond, another sees a sine curve. Since a sine curve is

easier to draw, we shall make use of it. This schematic wave has four properties: amplitude A, wavelength λ, frequency ν, and velocity of propagation v.

The amplitude of a wave is its maximum height. The definition of the wavelength is clear from the drawing: it is the distance between two similar points of any two consecutive waves. The velocity of propagation evidently requires no special explanation. To find out what the frequency means we shall observe the motion of a wave during one second.

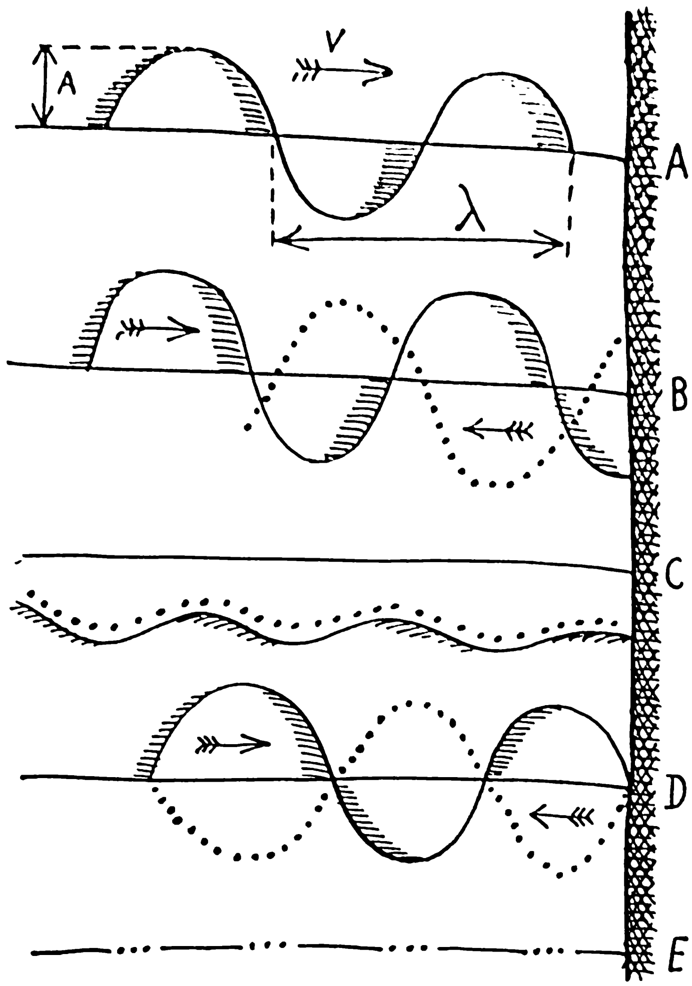
During this time the wave travels a distance of v centimetres, its velocity being v cm/s. Counting the number of wavelengths in this distance (or dividing the distance v by the wavelength λ) we obtain the frequency of the wave (or radiation). Thus

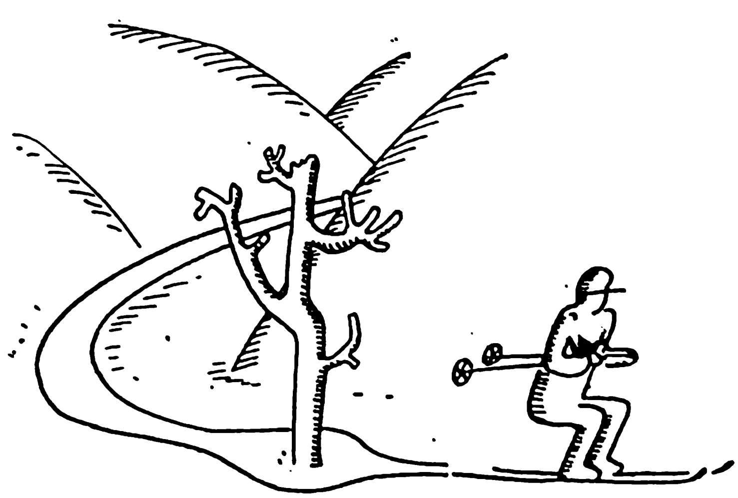
$$\nu = \frac{v}{\lambda}$$

One of the most important properties of waves is their capacity for *interference*. What is the essence of this phenomenon?

Assume that we throw a handful of peas with all the force we can muster against a wall so that they rebound quite a distance from the wall. Assume that we managed to throw the peas uniformly so that exactly eight peas strike each area of one square centimetre of the wall in one second. Now select any area of one square centimetre in the space between you and the wall, in the path of the flying and rebounding peas. If we count the number of peas flying through this area both ways, we shall find that it will always be 16.

What happens when a wave is reflected from a wall? Let us carefully examine the drawing. First a wave propagates without hindrance to the right (A); then it reaches the wall and is reflected (B). But we do not see two separate waves; we see the result obtained when





the two waves—direct and reflected—are added together. This result depends upon the way the wave contacts the wall (C). Sometimes, this happens in such a way that the crests of one wave exactly cancel the troughs of the other and produce darkness (D and E). This capacity of a wave to cancel itself is precisely

what is called interference. A wave can always be distinguished from a stream of particles by this feature.

Still another property of a wave that distinguishes it from particles is *diffraction* or, to put it more simply, the capacity of a wave to bend around an obstacle if its size is commensurate with the wavelength. In addition, if the obstacle is small enough, the wave may divide into two, due to diffraction upon meeting the obstacle, go around it from both sides and, uniting again, cancel itself in exactly the same way as when the direct and reflected waves are added together.

Exactly in this manner, by observing interference and diffraction of X rays and other kinds of radiation, it was established that they are all waves, though of different length. The wavelength of radiation is that principal feature by means of which we can distinguish between the various types of electromagnetic radiation quantitatively.

Radio waves are of greatest length: from several kilometres to several centimetres.

Thermal radiation is of shorter wavelength: from 1 cm to 10^{-2} cm.

Waves of visible light are still shorter: from approximately 4×10^{-5} to 8×10^{-5} cm.

The shortest wavelengths are those of X rays: from 10^{-7} to 10^{-9} cm.

All these kinds of radiation propagate at the same velocity, that of light: $c=3\times10^{10}$ cm/s. It follows that it is very easy to find the frequency of each kind of radiation from the formula $\nu=\frac{c}{\lambda}$. It will obviously be the highest for X rays and the lowest for radio waves.

We must realize, however, that any radiation is, of course, not the sine curve shown in the figure, but a *phy-*

sical process whose principal characteristics (for instance, periodicity) can fortunately be expressed in the language of such simple models.

Each kind of radiation has its specific features. Let us focus our attention, for the time being, on the kind that is most important to us and to which we are most accustomed, that is solar radiation. Since it obeys the same laws as any other kind of radiation, it will help us subsequently to understand the laws of thermal radiation which turned out to be so significant in the history of quantum mechanics.

When you bask in the sun on a beach, it is hardly likely that you ponder over the kinds of waves its rays are made up of. Sometimes, perhaps, you may ask yourself why you may get sunburned in the mountains and why you cannot get tanned in the late afternoon. Sir Isaac Newton (1642-1727) lived in England where there is not so much sunshine. Nevertheless, he wondered what sunlight consisted of. Following Marcus Marci (1595-1667), a professor of medicine at the Karlov University in Prague, Newton performed an experiment in 1664 that is known now to every schoolboy. He passed a ray of sunlight through a prism and observed the rainbow of colours thrown on the wall behind the prism. This band of colour is known as the spectrum of a ray of sunlight.

Each colour of the rainbow-spectrum corresponds to its own wave of solar radiation: red light has the longest wavelength, it is 7×10^{-5} cm; that of green light is 5×10^{-5} cm and of violet 4×10^{-5} cm. Besides visible rays, the solar spectrum contains others, for instance infrared rays (with a wavelength even longer than red light) and ultraviolet rays (whose wavelength is shorter than that of violet light). Consequently, ultraviolet rays have the maximum and infrared rays the minimum frequency in sunlight.

The relative brightness of the various colours in a radiation spectrum is not the same and depends upon the temperature of the radiating body. For example, in solar radiation there are mostly yellow rays. Thus, the spectrum of any radiation shows, firstly, of what kinds of rays it consists, and secondly, how much there are of each kind.

The spectral composition of a sunray is changed as it passes through the earth's atmosphere because the various rays of the solar spectrum are differently absorbed by the atmosphere. Ultraviolet rays, for instance, are absorbed to the greatest degree. The layer of air is thinner on a mountain top, more ultraviolet rays get through and therefore you can get sunburned more readily on a mountain than in a valley.

Though this fact is widely known, we nevertheless point out that sunburn is caused by ultraviolet rays and not, by any means, green or red rays. This is important for what follows. But to burn something you must in any case expend some energy. Evidently, the greatest amount of energy is carried by the waves of maximum frequency, that is ultraviolet, and not infrared rays (though it is precisely the latter that are called heat waves). Here we have established a fundamental fact.

To sum up, every body consists of atoms which, for the time being, we picture as small spheres 10^{-8} cm in diameter and of various weights: from 10^{-24} to 10^{-22} grams. They move very rapidly, vibrate and collide with one another. The velocity of their motion increases with the temperature of the body they constitute. This thermal motion leads to an entirely new phenomenon: thermal radiation whose properties are, as yet, unknown to us.

Let us now return to the iron poker which we left in the furnace. The hotter the furnace, the greater the

thermal radiation emitted by the poker. This had always been known, of course, but the quantitative law was only established empirically in 1879 by Josef Stefan (1835-1893) and theoretically in 1884 by Ludwig Eduard Boltzmann (1844-1906). They found that with a rise in temperature the total amount of radiated heat grows very rapidly: proportionally to the fourth power of the absolute temperature of the body.

What will happen now if we put a cobblestone into the furnace (instead of a poker) as they used to do in old classical Russian baths? Will its energy of radiation differ from that of an iron poker? In 1859, Gustav Robert Kirchhoff (1824-1887) proved that it would not if the temperature of the furnace was the same in both cases. He proved something more, but to understand this something, it will be necessary to break off our account and to examine more intently the radiation flux emitted by a heated body.

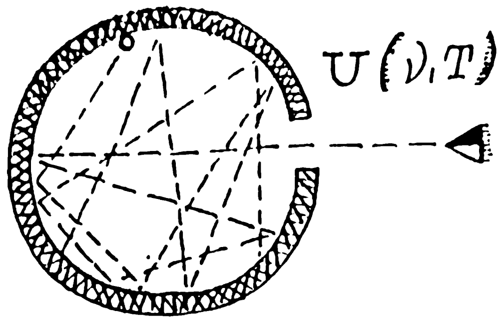
Like sunlight this flux is nonuniform. In the first place any thermal radiation consists of rays of various wavelengths, and secondly, their contributions to the total radiation flux are different. If both these characteristics are known to us, we can contend that we know the *spectral composition* of the radiation.

To emphasize the fact that the share of radiation with the frequency ν in the total radiation flux depends upon the temperature T, the following formula is usually written:

$$U = U(\nu, T)$$

Of course, if we change the temperature of the body, the spectral composition of its thermal radiation will likewise change. The quantitative laws of this change were established in 1893 by Wilhelm Wien (1864-1928).

But even at the same temperature, different bodies radiate differently. This can be convincingly proved



by simultaneously heating, for instance, steel and stone balls in a dark room. It was soon discovered, however, that if hollow balls were heated instead of solid ones, and if the radiation was observed through a small hole in their walls, the spectral composition of this radiation no longer depended on the material of the ball. Such a spectrum was named a *blackbody spectrum*.

The origin of this somewhat unusual name is not difficult to understand. Imagine that we are not heating a hollow ball but are illuminating it from outside. Look into the ball and you will always see a black hole, regardless of the material of the ball. The reason is that all rays that enter the ball are reflected and re-reflected inside, and almost none of them emerge again.

A practical example of a black body is an ordinary, or still better, an openhearth furnace. Incidentally, if you have ever looked into an openhearth furnace, you will probably have noted an interesting phenomenon: the steady light shining out of the furnace opening does not allow us to distinguish the details of objects lying inside. Our newly acquired knowledge on radiation should enable us now to understand this fact as well.

Two balls of equal size, one of stone and the other of steel, can easily be distinguished in the sunlight because they shine so differently. A steel ball reflects many more rays than a stone one does. (This, by the

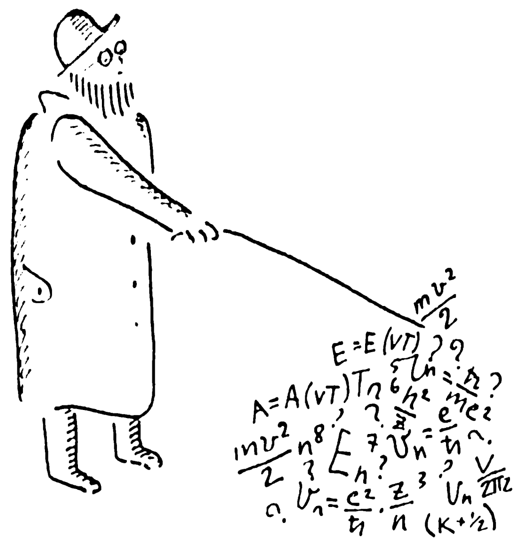
way, is one of the reasons why it was more expedient to heat large cobblestones in the old Russian baths than steel balls.)

If we charge the stone and steel balls into a furnace where they are not only heated and begin to radiate, but also absorb and reflect the radiation of other bodies, we shall see (naturally, if we look into the furnace before the balls melt) two absolutely identical balls. Why? Because the stone ball, although it radiates more of its "own" rays, absorbs more rays from other bodies. The steel ball, on the contrary, radiates less of its own rays and reflects more rays from other bodies. Therefore, the total flux of rays (their own and those from other bodies that they reflect) is exactly the same from both balls. This makes it impossible to distinguish them from each other, and even from the walls of the furnace in which they lie.

It was precisely this rigorous law that Kirchhoff established in 1859: the ratio of the emissive (or radiating) power of bodies to their absorptive power is a universal function $U=U(\nu, T)$, independent of the nature of the bodies. The function $U=U(\nu, T)$ (known also as the spectral function) contains almost all the information on the properties of thermal radiation. In particular, the colour of a heated body is determined by the waves which it emits in the greatest quantity.

The significance of the function $U=U(\nu, T)$ was realized at once, in Kirchhoff's time, but for 40 years no one could find a formula for it that would properly describe the experimentally measured curve. These attempts never ceased; evidently, the search for the Absolute has always attracted the minds of men.

In our narrative we have reached the threshold of the revolution accomplished in physics by Max Karl Ernst Ludwig Planck (1858-1947). But before we go on to explain what it was all about, let us recall one



feature of thermal radiation that has already been mentioned. This feature is the change in the colour of bodies when they are heated.

As long as the temperature of the body is low, it radiates but does not glow, does not give off light, that is it emits only heat and infrared waves which are invisible. As the temperature is raised the body begins to glow, first with a red colour, then orange, yellow, etc. For example, at six thousand degrees Celsius (Centigrade), mostly yellow rays are emitted. This feature, incidentally, helped to establish the fact that this is the temperature of the sun's surface.

Note that in the case with sunburn, the higher the frequency, the greater the energy delivered by the radiation. And now what do we find? The greater the energy expended in heating a body, the higher the frequency of the emitted waves. Consequently, *some kind of relationship exists between the frequency and the radiant energy.*

QUANTA

At the end of last century, Max Planck sought for a universal formula for the blackbody spectrum. What could his line of reasoning have been? Not only is

thermal radiation produced by the motion of atoms, but it also acts on them because it carries energy. As a result of such mutual influence, a thermal equilibrium is set up inside a black body: the amount of heat the atoms receive from outside equals the amount of energy they give up by radiation. From the kinetic theory of matter, Planck knew that the mean vibrational energy E_{vib} of the atoms is proportional to the absolute temperature T. Thus

$$E_{vib} = kT$$

where $k = 1.38 \times 10^{-16}$ ergs per degree is the proportionality factor called Boltzmann's constant.

Now recall that the radiant energy increases with the frequency. This, of course, Planck also knew. But how does it increase? He assumed the simplest relationship: that the radiant energy E_{rad} is *proportional to its frequency*:

$$E_{rad} = h\nu$$

where h is another proportionality factor. (This idea is so simple that it cannot be proved and explained by still simpler concepts. However, a classical simplicity is inherent in all such brilliant ideas.)

After making this assumption, Max Planck guessed the formula for the spectral function $U = U(\nu, T)$. Yes, he actually *guessed* it. But it was not at all that simple, Planck had racked his brains over the formula for two years.

On October 19, 1900, there was a regular meeting of the German Physical Society. Physicists Heinrich Rubens and Ferdinand Kurlbaum reported on their new, more accurate measurements of the blackbody spectrum. After the report, a discussion took place in which the experimenters complained over the fact that not one of the known theories could explain the

results they obtained. Planck proposed that they try to use his formula. That same evening, Rubens compared his measurements with the results given by Planck's formula and found that it correctly described the blackbody spectrum to the smallest details. Next morning, he informed his colleague and close friend Planck and congratulated him with his success.

Planck, however, was a theoretician and valued, therefore, not only the final results of a theory, but its intrinsic perfection as well. Moreover, he did not yet know that he had discovered a new law of nature; he thought it could be derived from previously known laws. Hence, he tried to substantiate this law of radiation proceeding from the principles of kinetic theory of matter and thermodynamics. After two hectic months of continuous calculations and nerve strain, he succeeded. But at what cost!

In his calculations he was forced to assume that radiation is emitted in discrete portions (or quanta), whose size is determined exactly by the formula $E=h\nu$ which he had guessed two months before.

In that case, and only in that case, could he obtain the correct formula for the radiation spectrum.

The relationship $E=h\nu$ cannot be substantiated by any logical deduction; nor can the law of gravity. They just exist; that just happens to be the way the universe is arranged. And what is more, only if we accept and employ them can we explain other phenomena observed in nature. This includes the blackbody spectrum as well.

Formally Planck's assumption was clear and simple to the extreme, but in essence it contradicted all the previous experience of physics

and intuition. Recall that we have repeatedly emphasized that radiation is a wave phenomenon. If so, then energy in this process can only be transferred continuously, and not in discrete quantities or quanta. Planck was aware of this unavoidable contradiction more than any other physicist. He was 42 years old when he derived his famous formula, but he suffered from the logical imperfection of his own theory almost all the rest of his long life. This feeling of imperfection was dulled in subsequent generations of physicists; they already knew the end result and had learned to think along new lines.

But Planck had been brought up in the traditions of classical physics and belonged, heart and soul, to its rigorous unhurried world. It turned out that, in solving this long-standing riddle in radiation theory, he had impaired the logical orderliness of all classical physics. "Have we not paid too dear a price to achieve the solution of this, essentially very special, case?" This was a haunting thought that troubled Max Planck tremendously. Later, in his Nobel Prize Lecture, he recalled that to him the recognition of the reality of quanta was equal to the "impairment of all causal relationships".

Only considerably later, in 1927, did the new science of quantum mechanics show that no contradiction existed. But that was still many years in the future.

On December 14, 1900, in the conference hall of the German Physical Society, a new science—the study of quanta—was born. Drily and in great detail, Max Karl Ernst Ludwig Planck, full professor of physics, read a special paper before a small audience. It was called "On the Theory of the Energy Distribution Law of the Normal Spectrum".

Very few people realized that day the grandeur of the moment. The bad weather or the logical contradictions of the theory probably occupied the thoughts of the learned audience to a greater degree. Acknowledgement came much later. And still later did scientists understand the significance of Planck's constant h for the whole world of atoms. It turned out to be very small in value:

$$h = 6.62 \times 10^{-27} \text{ erg-s}$$

but it opened the door to the world of atomic phenomena. And always, when we want to go from the world of customary and classical physics to the unusual quantum world, we have to pass through this narrow doorway.

ROUND AND ABOUT THE QUANTUM

DEMOCRITUS' APPLE

So far we have found out very little about atoms, but even this knowledge is sufficient to solve the problem put by Democritus: how many times will it be necessary to divide an apple and its parts consecutively to reach its "atom"?

Assume that Democritus held a large apple, one about ten centimetres in diameter. Then its volume was about $V = 10^3$ cm^3 and was reduced by one half in each division. After the nth division, its volume V_n became

$$V_n = \frac{V}{2^n} = \frac{10^3}{2^n} = \frac{10^3}{10^{0.3n}} = 10^{3-0.3n}$$

According to Loschmidt's evaluation, the volume of an atom is about $(10^{-8}\text{ cm})^3 = 10^{-24}$ cm^3. We shall

stop halving our pieces of apple when the volume V_n is equal to the volume of an atom, that is under the condition

$$10^{3-0.3n} = 10^{-24}$$

From this we readily find that $n=90$, i.e. at the 90th stage of division, Democritus would already have reached his aim. Not so much, is it?

Even if we take into account the fact that he was busy thinking profoundly and hence did not hurry in cutting up the apple, a half an hour seems to be quite sufficient for this delicate operation.

ISAAC NEWTON ON ATOMS

"All these things being considered, it seems probable to me that God in the beginning formed matter in solid, massy, hard, impenetrable, movable particles, of such sizes and figures, and with such other properties, and in such proportion to space, as most conduced to the end for which He formed them, and that these primitive particles being solids, are incomparably harder than any porous bodies compounded of them; even so very hard as never to wear or break in pieces; no ordinary power being able to divide what God Himself made one in the first creation!

"It seems to me, further, that these particles have not only a *vis inertiae*, accompanied with such passive laws of motion as naturally result from that force, but also that they are moved by a certain active principle, such as that of gravity, and that which causes fermentation, and the cohesion of bodies. These principles I consider, not as occult properties, supposed to result from the specific forms of things, but as general laws of nature, by which the things themselves

are formed; their truth appearing to us by phenomena, though their causes be not yet discovered. For these are manifest qualities, and their causes only are occult."

PLANCK ON THE QUANTUM

Max Planck's Nobel Prize Lecture, delivered to the Royal Swedish Academy in Stockholm on June 2, 1920, when he was awarded the Nobel Prize in physics, was called "The Genesis and Present State of the Development of Quantum Theory". The following two extracts are from this lecture:

"The foundering of all efforts to bridge the chasm soon left little doubt. Either the quantum of action was a fictional quantity, then the whole deduction of the radiation law was in the main illusory and represented nothing more than an empty non-significant play on formulas, or the derivation of the radiation law was based on a sound physical conception. In this case, the quantum of action must play a fundamental role in physics, and here was something entirely new, never before heard of, which seemed called upon to basically revise all our physical thinking, built as this was, since the establishment of the infinitesimal calculus by Leibnitz and Newton, upon the acceptance of the continuity of all causative connections...."

"Be that as it may, in any case no doubt can arise that science will master the dilemma, serious as it is, and that which appears today so unsatisfactory will in fact eventually, seen from a higher vantage point, be distinguished by its special harmony and simplicity. Until this aim is achieved, the problem of the quantum of action will not cease to inspire research and fructify it, and the greater the difficulties which oppose its solution, the more significant it fin-

ally will show itself to be for the broadening and deepening of our whole knowledge in physics."

Planck had no doubts about the significance of his discovery (he told his son, "Today I have made a discovery as important as that of Newton"), but he was too modest to make a show of it. Perhaps that is the source of the misled opinion that Planck "did not seem to know what he had done, when he did it". The cited extracts from his Nobel Prize Lecture once again disprove this delusion.

Chapter Two

RAYS * ATOMS * ELECTRONS * ATOMS, ELECTRONS, RAYS

Neither the names of rulers nor the dates of their reign are of prime interest to us in the history of mankind (though without such data history would not exist at all), but the birth, flourishing and decline of civilizations and the evolution and essence of ideas which have directed the wills of men for centuries and determined the nature of their interrelations. In history we try to understand the reasons for the renewal of ideas, and the circumstances under which they become extinct.

In exactly the same way, the history of physics is not simply a collection of facts, but a coherent picture of the origin and development of physical ideas, without which science may seem to be a random set of formulas and concepts.

Truths are fruitful only when there is a logical internal connection between them, a connection that can be observed only in their development.

Even savages at the lowest level of development have a history of their own. When history is lost, time gets "out of joint" and people cease being people,

just as a person irreversibly degenerates upon losing his memory.

The history of physics is a necessary element in the education of a physicist. Without it he will remain a mediocre scientist all his life. For others it is mainly a history of human destinies which are sometimes as extraordinary as the destinies of rulers and military conquerors.

To understand the completeness and elegance of the concepts of modern physics, it is necessary to retrace their sources and their ways of development. Only then will they become near and understandable, just as near to you as your native land whose history and culture you have imbibed from early childhood.

The famous mathematician Felix Klein (1849-1925) once said that the fastest and most reliable way to master any science is to follow through its whole path of development yourself. This is not the simplest way, but it is the most interesting one and we have chosen it precisely for this reason.

It is especially important for us to retrace the evolution of the concepts of *rays*, *atoms* and *electrons*, so that at the end of our journey we can feel the beauty of their synthesis.

RAYS

A sunbeam, if we follow it observantly, can lead us right up to the threshold of quantum physics. It is quite probable that this transition does not seem convincing to you as yet. But the feeling of arbitrariness that one experiences when he first becomes acquainted with Planck's theory is really deceptive. Planck's formula is not the result of speculation; it appeared only after a prolonged analysis of precise experiments. Analysis alone is insufficient, of course, to devise this

formula. Also required are the power of thought, flight of fancy and boldness in the face of the unexpected consequences of the theory.

Before Planck, Lord Rayleigh, Jeans and Wien had proposed various formulas for describing the black-body spectrum. But each time, after carefully measuring this spectrum, the experimental physicists Otto Lummer (1860-1925) and Ernst Pringsheim (1859-1917) flatly rejected each new formula as being imperfect. Only Planck's formula satisfied them; it strikingly coincided with the results of their experiments, though this did not make it any clearer.

Let us follow the example of these physicists and examine the structure of a sunbeam more attentively than we have done before. Further on we will see how much information it carries, and our task is to learn to read it.

If we pass a ray of sunlight through a prism, a spectrum will appear on a screen behind the prism. This is a familiar phenomenon; we have become used to it in two hundred years. On the face of it there are no sharp boundaries between the different parts of this spectrum: red gradually goes over to orange, orange to yellow, etc.

That is what everyone thought until in 1802, the English physician and chemist, William Hyde Wollaston (1766-1828), examined this spectrum more intently. For this purpose he built the first spectrograph with a slit and with it he discovered several distinct dark lines which crossed the solar spectrum without any apparent order at various places. He attached no great importance to these lines. He supposed they were due either to the quality of the prism, or the source of light, or to other secondary causes. The lines themselves he considered to be of interest only because they separated the coloured bands of the spectrum

from one another. Subsequently, they were named *Fraunhofer lines* after their real investigator, and not their discoverer.

Joseph von Fraunhofer (1787-1826) did not live very long, but his biography is amazing. At eleven years of age, after the death of his parents, he became an apprentice to a master craftsman in the grinding trade. He had to work such long hours that he had no time left to attend school. As a result, up to his fourteenth year he could neither read nor write. One day, however, the ramshackle house of his master collapsed and, as Fraunhofer was being extracted from the wreckage, wonder of all wonders, the Crown Prince of the country rode by in his carriage. He was sorry for the young fellow and presented him with a considerable sum of money. It proved sufficient for Joseph to buy himself a grinding machine and also to start going to school.

This was during the Napoleonic wars in Europe, a time of great changes. Meantime, Fraunhofer went to school in the provincial town of Benedictbeuern near Munich, ground optical glass and painstakingly investigated the dark lines in the solar spectrum. He found 574 lines, labeled the most prominent ones by letters of the alphabet and indicated their exact location in the spectrum. Their positions were strictly invariable. A sharp double line, in particular, called the D line by Fraunhofer, always appeared at the same place in the yellow region.

Fraunhofer established another important fact: he found *a bright double yellow line* in the spectrum of the flame of a spirit lamp which always occupied exactly *the same place as the dark D line in the solar spectrum.* The significance of this fact was appreciated only after many years had passed.

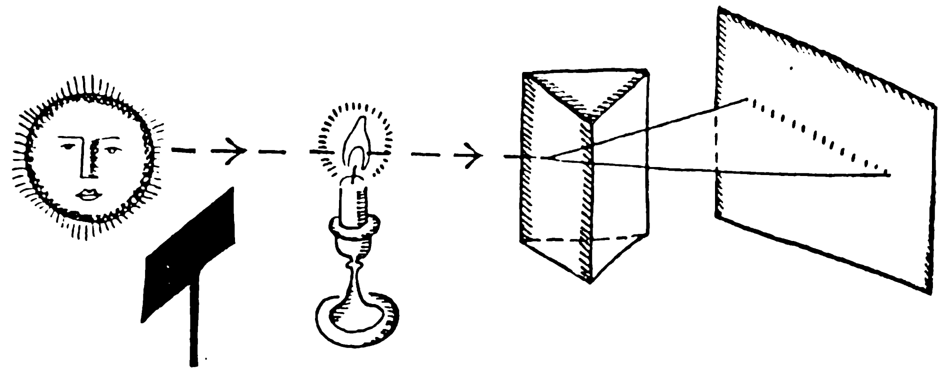
In 1819 Fraunhofer moved to Munich where he be-

came a professor, a member of the Academy of Sciences and, in 1823, was appointed the conservator of the physical cabinet. Continuing his observations of the dark lines in the solar spectrum, he was finally certain that they are not due to an optical illusion, but to the very nature of sunlight. Induced by the strangeness of these lines to further investigations, he later discovered them in the spectra of Venus and Sirius as well.

Joseph von Fraunhofer died and was buried in Munich in 1826. His gravestone bears the inscription. *Approximavit sidera*, that means, "He brought the stars closer". But his best monument is his discoveries.

Of Fraunhofer's discoveries, the most important to us just now are his observations of the double D line. Then, in 1814, when he published his investigations, no especial attention was paid to his observations. His work was not in vain, however: 43 years passed and William Swan (1818-1894) established that the double yellow D line in the spectrum of a spirit lamp flame appears only in the presence of the metal sodium. (Its traces as a component of common salt can almost always be found in various substances, as well as in a spirit lamp.) As many other scientists before him, Swan did not realize the significance of his discovery and therefore did not say the decisive words: "This line *belongs* to the metal sodium."

This simple and important idea came only two years later (in 1859) to two professors: Gustav Robert Kirchhoff (1824-1887) and Robert Wilhelm Bunsen (1811-1899). In Heidelberg, in the old university laboratory, they conducted a comparatively simple experiment. Before their experiment, other investigators had passed either only sunlight or only light from a spirit lamp through a prism. Kirchhoff and Bunsen passed



both at the same time and discovered a phenomenon that deserves a more detailed description.

They used what is now called a Bunsen burner as the source of light introducing various materials, for instance sodium in the form of ordinary salt, into its flame.

If only a ray of sunlight fell on the prism, they saw on the spectroscope scale a solar spectrum with the dark D line in its usual place. This dark line was also in the same place when the investigators put a Bunsen burner in the path of the ray. But when they put an opaque screen in the path of the sun's ray and illuminated the prism only with light from the burner, the bright yellow D line of sodium appeared in place of the dark D line. When Kirchhoff and Bunsen removed the screen, the D line became dark again.

Then they substituted the light of some body heated to incandescence for the ray of sunlight—the result was always the same: a dark line appeared in place of the bright yellow one. This meant that *the flame of the burner always absorbed the rays which it itself emitted.*

To understand why this event excited the two professors, let us follow the course of their reasoning.

The bright yellow D line appears in the spectrum of the Bunsen burner flame in the presence of sodium.

At exactly the same place in the solar spectrum, a dark line of unknown origin is observed.

The spectrum from the rays of any incandescent body is continuous; it has no dark lines. However, if we pass these rays through the flame of a Bunsen burner, then the spectrum will not differ in any manner from the solar spectrum: it will also have the dark line and in exactly the same place. But we are almost sure of the origin of *this* dark line. In any case, we can guess that it belongs to sodium.

Consequently, depending upon the conditions under which it is observed, the D line of sodium can be either bright yellow or dark on a yellow background. But in both cases the presence of this line (no matter whether it is yellow or dark) means that there is sodium in the flame of the burner.

Since such a line of the spectrum produced by a Bunsen burner flame in transmitted light coincides with the dark D line in the solar spectrum, there must be sodium on the sun. This sodium is contained in the gaseous outer envelope which is illuminated from inside by the incandescent core of the sun.

The short article (only two pages long), written by Kirchhoff in 1859, contained four discoveries:

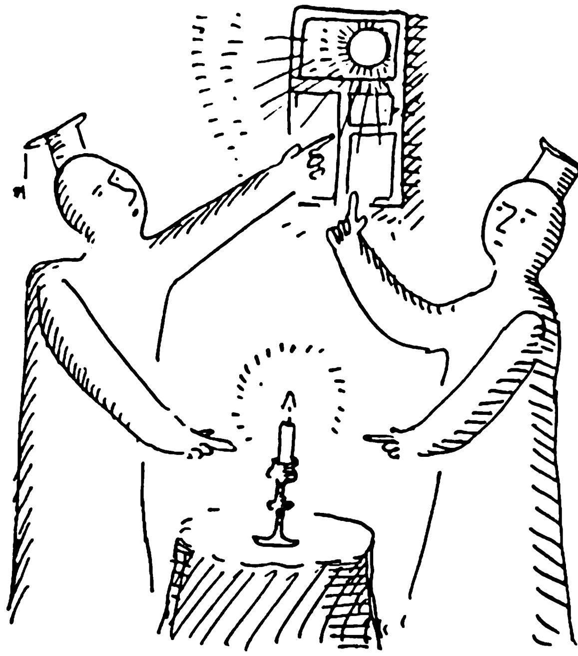
each element has its own line spectrum, i.e. a strictly definite set of lines;

these lines can be used to analyse the composition of substances not only on the earth, but on the stars as well;

the sun consists of a hot core and a comparatively cooler atmosphere of incandescent gases;

there is sodium on the sun.

The first three discoveries were soon confirmed, including the hypothesis on the structure of the sun. An expedition, headed by the astronomer Pierre Jules César Janssen (1824-1907), was sent by the French



Academy of Sciences to India in 1868. It was found that in a total eclipse of the sun, at the moment when its incandescent core is closed by the moon's shadow and only the corona gives light, all the dark lines in the solar spectrum flare up with bright light.

The second hypothesis was not only confirmed by Kirchhoff and Bunsen in the following year, but was used by them to discover two new elements: rubidium and cesium.

Subsequently, this modest observation of the double D line of sodium led to the birth of *spectral analysis*, by means of which we can determine the chemical composition of distant galaxies, measure the temperature of stars and their speed of revolution, etc.

All this is extremely interesting, but, for the present, the main thing that we must find out is: what have Kirchhoff and Bunsen's discoveries contributed to the science of the atom, and what is their relation to our previous knowledge of the atom?

We now know of two kinds of spectra: continuous (or thermal) and line spectra.

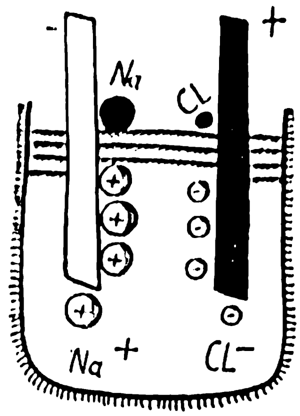
A thermal spectrum contains all wavelengths, it is radiated when solid bodies are heated and it does not depend upon the nature of the bodies.

A line spectrum consists of a set of sharply defined lines; it appears upon heating gases and vapours (when the interaction is weak between the atoms) and, what is especially important, the set of lines is unique for each element. Moreover, the line spectra of elements do not depend upon the kind of chemical compound made up of these elements. Hence, we must look for an explanation of their spectra in the properties of atoms.

The fact that elements uniquely and quite definitely determine the kind of line spectrum observed was soon recognized by everybody; that the same spectrum characterizes a *single atom* was not realized at once, but only in 1874 thanks to the work of the famous English astrophysicist Sir Joseph Norman Lockyer (1836-1920). [Incidentally, the same ideas were expressed earlier by Maxwell (in 1860) and Boltzmann (in 1866).] And when they did realize it, they immediately reached the inevitable conclusion: since a line spectrum is originated *inside* a separate atom, *the atom must have a structure*, i.e. it must have component parts!

ATOMS

In 1865, when Joseph Loschmidt's works appeared, not much was known about atoms. They were pictured as small solid spheres about 10^{-8} cm in size and weighing from 10^{-24} to 10^{-22} grams. Each such sphere could be ascribed an atomic weight, i.e. a number indicating how many times it is heavier than an atom of hydrogen. For example, the atomic weight of oxygen equals 16 and that of helium equals 4. It readily



follows that 1 gram of hydrogen, 4 grams of helium or 16 grams of oxygen (or, as it is customary to say in chemistry, one gram-atom of any substance) contains the same number of atoms of hydrogen, helium or oxygen. This number $N = 6.02 \times 10^{23}$, called the Avogadro number, is related to Loschmidt's number by the equation

$$N = 22413.6\ L$$

Thus the Avogadro number is the number of molecules in 22.4136 litres of a gas at normal atmospheric pressure and the temperature of melting ice.

The concept of atoms as being solid spheres was adequate to explain numerous facts from chemistry, and the theory of heat, and the structure of matter. By 1870, however, the idea that atoms consist of still simpler particles had already taken shape, and physicists started to look for them. First of all they investigated the *electrical properties* of the atom.

As a rule all substances are electrically neutral. Under certain conditions, however, they begin to display electrical properties, for instance when you rub glass with wool, amber with silk, etc. These properties are especially distinctly manifested in electrolysis phenomena.

If two electrodes are immersed in a molten salt (for instance, common salt NaCl) and their upper ends are connected to the poles of a battery, a change will take place in the melt. Pure metallic sodium will be deposited on the cathode (the electrode connected to the negative pole of the battery) and bubbles of chlorine gas will be liberated at the anode. This means that in the melt the sodium atoms are positively charged and the chlorine atoms negatively. Therefore, when acted upon by the electric field, they move in opposite directions.

In 1834, Michael Faraday (1791-1867) established the quantitative laws of this phenomenon. He found that if the same amount of electricity, equal to 96,484.52 coulombs, is passed through solutions of various substances whose molecules are made up of monovalent atoms, exactly one gram-atom of the substances is always deposited on each electrode. For example, 23 grams of metallic sodium and 37.5 grams of chlorine gas are liberated from a melt of common salt.

Faraday's law of electrolysis is easy to understand if we assume that a definite charge is linked to each atom in a melt of NaCl, and that for the ions Na^+ and Cl^- these charges are equal and of opposite sign. (The name *ion*, first used by Faraday in his works for such "charged" atoms, is from a Greek word meaning "wanderer". It was suggested to Faraday by William Whewell, author of the famous *History of the Inductive Sciences, from the Earliest to the Present Times*, who also suggested the terms *anion* and *cation*, and the now familiar *anode* and *cathode*.) The charge carried by one ion equals $e=4.802\times10^{-10}$ esu (cgs electrostatic unit of charge).

This value is very small, but we are becoming accustomed to such small values. More astonishing is anoth-

er fact: no charges smaller than this elementary charge e have ever been found. In 1891, the Irish physicist George Johnstone Stoney (1826-1911) had the good fortune to suggest the name for this minimum possible charge that it is known by today. He called it an *electron*.

ELECTRONS

In the beginning, the concept of a particle was not linked to this term. It merely served to designate that minimum amount of charge that can be carried by an ion of any atom. The latent idea, however, that an electron is a particle, always existed. Let us analyse the process of electrolysis: an ion of sodium (Na^+), travelling in the solution due to the action of the electric field, approaches the cathode. The cathode has a surplus of negative charges and therefore, at the instant it is reached by the ion Na^+, the latter takes one negative charge from the cathode and, without any change in weight, is deposited as a neutral atom of sodium.

Try to imagine, now, the instant of transfer of the negative charge from the cathode to the ion Na^+. What is added to the ion when, *without a change in weight*, it becomes neutral?

It is quite difficult to picture this process unless we assume that the elementary charge can exist outside of the atom as well. This difficulty was realized, of course, by all investigators, but an acknowledgement of the atomic structure of electricity seemed even more difficult, because this completely destroyed the convenient and customary conception of electricity as a certain fine fluid that readily penetrated all bodies. In his famous "Treatise on Electricity and Magnetism" (1873), Maxwell allows that in an electrolyte the mole-

cules are charged with a definite amount of electricity but immediately admits that this alluring hypothesis leads to very great difficulties.

On April 5, 1881, at a meeting of the Royal Institution devoted to the memory of Michael Faraday, Hermann Ludwig Ferdinand von Helmholtz (1821-1894) read a paper called "On the Modern Development of Faraday's Conception of Electricity". In this paper, Helmholtz first clearly formulated the idea of the "molecular structure of electricity". "If we accept the hypothesis," he said, "that the elementary substances are composed of atoms we cannot avoid concluding that electricity also, positive as well as negative, is divided into definite elementary portions, which behave like atoms of electricity."

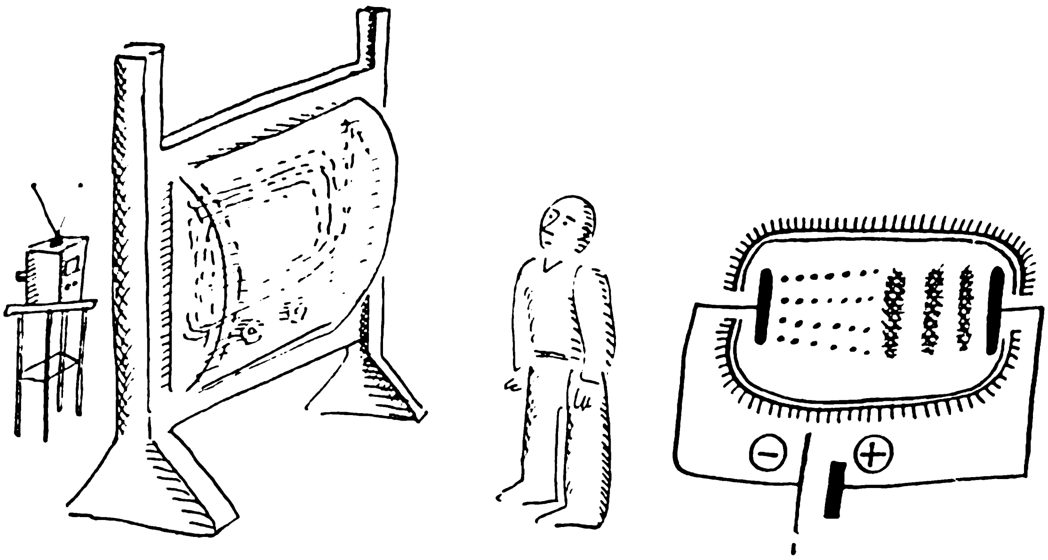
As such, of course, this idea was not new even then. Way back in 1749, the great American statesman, scientist and inventor, Benjamin Franklin suspected something like this, but his guess was not based on any known facts and therefore did not lead to any new consequences. In 1871, the German physicist Wilhelm Eduard Weber (1804-1891) returned to Franklin's idea, but met no sympathy. By his time, so much was already known about electricity that no hypothesis could be accepted without definite proof; knowledge presupposes responsibility. It was necessary to obtain experimental proofs of the idea of electrons. Attempts were made to find them in the conduction phenomena of gases.

Imagine a glass tube filled with some gas (for instance, neon) and sealed at both ends together with wires (usually of platinum). If we connect these two wires to different poles of a battery, one to the negative pole (cathode) and the other to the positive pole (anode), current will flow in the circuit, exactly in the same manner as when we use an electrolyte. Probably,

it was just this analogy with electrolysis that incited Faraday in 1838 to make the prototype of such a tube (Faraday's "electric egg"). As we shall see, the analogy is entirely superficial, but the phenomenon of gas conductivity as such was so interesting that many investigators devoted their whole lives to a study of its properties.

About the middle of last century, Julius Plücker (1801-1868) (whose name is known now to every mathematician), abandoned his study of geometry, which found no recognition among his contemporaries, and became enthusiastic about experimental physics. When you feast your eyes on a glamourous display of many-coloured illuminated signs, you owe this sight to the work of a professor of mathematics of Berlin and Bonn. It was Plücker who invented these luminous tubes in 1858. (They were usually called Geissler tubes, after the famous German glassblower Heinrich Geissler [1814-1879], who was Plücker's technical assistant and became very expert in making such tubes; a half century later they were generally called Crookes' tubes.)

First of all Plücker established that the conductivity of the gas depends upon its concentration in the tube and increases if a part of the gas is exhausted from the tube. Each gas begins to glow with its own particular colour, so that the composition of the gas in the tube can be determined from its colour. (Plücker came to this conclusion even before Kirchhoff and Bunsen, but did not understand its significance.) If the tube is further evacuated a dark space appears near the cathode ("Faraday dark space"). As the pumping proceeds, improving the vacuum, the dark space spreads and finally fills the whole tube which, consequently, ceases to glow. But this dark space is alive; it is pierced by some kind of "rays" though they are invisible to



us (just as a flying bullet is invisible until it meets some obstacle).

A pupil of Plücker's, Eugen Goldstein (1850-1930), called this radiation *cathode rays* in 1876. Earlier, another of his pupils, Johann Wilhelm Hittorf (1824-1914), found that these rays were deflected in a magnetic field and finally, in 1879, Cromwell Fleetwood Varley (1828-1883) showed that they are negatively charged.

At first attempts were made to comprehend these phenomena by the language of wave concepts (although Varley had preferred the corpuscular point of view as far back as 1871). This tendency can be easily explained. Memories were still fresh of the famous argument between Newton and Huygens on the nature of light. Hence any attempts to explain the observed phenomena by corpuscular radiation was interpreted as a return to the Middle Ages.

Put yourself in the place of these investigators: you are in the seventies of the 19th century, you have on hand a set of interesting facts, but there doesn't seem to be any relations between them. On the one hand, the phenomenon of gas conduction closely resembles the electrolysis process, but, on the other hand, quite

incomprehensible things occur, for example, the conductivity increases with a reduction of the gas concentration in the tube. Moreover, only a stream of negative "rays" is observed; no positive ones.

There was need for a dominating idea.

Such an idea occurred as a result of the brilliant experiments conducted by William Crookes, the English physicist and chemist. This was an extremely interesting person, one who had the rare gift of foreseeing fundamental discoveries. Crookes did not have to earn a living and was completely devoted to science (which, however, did not keep him from believing in spiritism and the supernatural, or from becoming president of the Royal Society in 1913).

In the first place, he devised a still better evacuated tube. Now another, even darker region, called the Crookes dark space, was produced at the cathode. It also grew gradually until it filled the whole tube, after which the anode started to glow with a faint greenish light. That day in 1878, when this happened, can be regarded as the birthday of the cathode-ray tube, the main component of a modern television set. This alone would have ensured Crookes the grateful acknowledgement of posterity. But for Crookes himself this was only the beginning. He painstakingly investigated the properties of this radiation, which he called "radiant matter" (this term was introduced by Faraday back in 1816). Crookes sensed that he had come across an entirely new phenomenon of nature and proposed that it be called "a fourth state of matter (i.e. not solid, liquid or gas)". Crookes wrote:

"In studying this fourth state of matter we seem at length to have within our draft and obedient to our control the little indivisible particles which with good warrant are supposed to constitute the physical basis of the universe. We have seen that in some of its proper-

ties radiant matter is as material as this table, whilst in other properties it almost assumes the character of radiant energy. We have actually touched the borderland where matter and force seem to merge into one another, the shadowy realm between Known and Unknown which for me has always had peculiar temptations. I venture to think that the greatest scientific problems of the future will find their solution in this Border Land, and even beyond; here, it seems to me, lie Ultimate Realities, subtle, far-reaching, wonderful."

"The phenomena in these exhausted tubes reveal to physical science a new world—a world where matter may exist in a fourth state, where the corpuscular theory of light may be true, and where light does not always move in straight lines, but where we can never enter, and with which we must be content to observe and experiment from the outside."

To properly appraise Crookes' courage, we must recall that at that time scientists divided the whole universe into matter and ether, these two entities being opposite and incompatible: identified as matter were particles, and as ether, the medium whose vibration we perceive as rays of light.

Thus, Crookes' "radiant matter" would have to be a combination of uncombinable properties: those of rays and particles. A half century later anyone could see how right he had been, but at that time Sir Oliver Lodge, a contemporary and compatriot, wrote that Crookes' supposition shared the fate of those flashes of inspiration that are sometimes permitted authors but are subject to the mockery of orthodox science of their times.

Irrespective of the meaning that Crookes put into the concept of "radiant matter", his indisputable experiments discovered that it has the following amazing properties: it travels in a straight line; it causes

bodies to glow and can even melt them; it is deflected in electric and magnetic fields; it can pass through solids; and its mean free path in air is 7 cm while that of atoms is only 0.002 cm.

On the basis of these facts, William Crookes contended that cathode rays, or radiant matter, consist of a stream of negatively charged particles of a size much smaller than atoms.

It is evident that this hypothesis cleared up all the observed properties of cathode rays. It readily explains, in particular, the occurrence of the dark space at the cathode: the width of this space is simply the mean distance that electrons travel before colliding with atoms of the gas. This distance obviously increases as we exhaust the gas from the tube. But these propositions are not the main significance of the hypothesis; it became the lodestar in the bewildering sea of facts that had been accumulated up to that time by experimental physics.

Now physicists knew what direction to choose and what to look for. It was necessary, first of all, to separate out an "atom of electricity" and to determine its properties: charge, mass and size.

This required almost 20 years and the efforts of such famous physicists as Sir Joseph John Thomson (1856-1940), Sir John Sealy Edward Townsend (1868-1957), Wilhelm Wien (1864-1928), George Francis FitzGerald (1851-1901), Emil Wiechert (1861-1928), Jean Baptiste Perrin (1870-1942), and Robert Andrews Millikan (1868-1953). We cannot describe here all the ingenious and subtle experiments devised by these and other scientists. We shall simply observe how the hypothetical "atom of electricity" gradually acquired real properties until it became, at last, the foundation of physics.

To begin with Jean Perrin finally proved in 1895

that cathode rays are negatively charged. During the next two years it was found that their velocity is about one-tenth of the velocity of light, that is, approximately 10,000 times that of a rifle bullet or the velocity of thermal motion of atoms. Besides, these and all the other properties of these rays did not depend upon the composition of the gas in the tube. This meant that the cathode particles are the indispensable components of all atoms.

Finally, in 1897, J. J. Thomson managed to measure the electric charge e and the mass m of a single "atom of electricity".

The mass of these particles ($\approx 10^{-27}$ grams) turned out to be only about one-thousandth of the mass of an atom of hydrogen, and the charge ($e \approx 5 \times 10^{-10}$ esu) almost exactly equal to the charge of an ion hydrogen, measured in investigating electrolysis.

This was certainly unexpected. Judge for yourself: the phenomena of electrolysis and the conductivity of gases were studied by different branches of science which developed independently of each other and whose concepts took shape over a period of several scores of years. All of a sudden it was found that they are closely related. "Such facts in the history of science," said Nobel Prize winner Max von Laue, a pupil of Planck's, "are the strongest proof of its truth." Events of this kind are always festive occasions for physicists and we shall have the opportunity of passing through other such crossroads of science in our journey.

The history of the electron is exemplary in understanding the logical sequence of discoveries made in modern physics. Proceeding from observations, scientists propose *hypotheses* based on them. These hypotheses are tested again by *experiments* and finally the process is completed by a *theory*, which is a concise

explanation of specific phenomena on the basis of a few general principles. The hypothesis of the electron originated from the observations of Faraday, Plücker and Crookes. The fertility of this hypothesis was tested and proved by the experiments of J. J. Thomson and other physicists.

In the final stage, Hendrik Antoon Lorentz (1853-1928) had such implicit faith in the reality of the electron that he founded a theory on the basis of the hypothesis. The logical conclusions of his theory could again be tested.

This process is endless, but it is the only way to advance science.

But, let us return to 1897 when, after forty years of effort, the first "elementary particle" became an entity. This was the most important event in physics since the reality of the atom had been acknowledged. Physicists found out, in this year, that particles considerably smaller than atoms do exist, that they are constituents of all atoms, and that not only matter, but electricity as well has an atomic structure. All this signified that a *material carrier of the minimum charge really exists in nature.* In 1900, Paul Drude (1863-1906) suggested that this particle be called the *electron.*

Like the atom, the electron was not recognized at once. Far from it. In 1902, Sir Oliver Lodge wrote that the electron was a purely hypothetical charge, insulated from the atom. As late as 1920, the world-famous Röntgen forbade the workers of his institute even to utter the word.

Today, these doubts are difficult to understand.

Physicists, who believed in the reality of electrons from the very start, carefully measured its characteristics: the charge e and mass m. Thanks to their labours (especially to those of Robert Andrews Millikan, who

returned to this task periodically from 1909 to 1940) we now know these quantities with great accuracy:

$$m = 9.109558 \times 10^{-28} \text{ grams}$$
$$e = 4.803250 \times 10^{-10} \text{ esu}$$

And what about its size? What are the dimensions of an electron? This, alas, is something we still know nothing about. We don't even know whether this question has any precise meaning. To determine the properties of an electron we investigate its interaction with other particles or with fields. But, to understand the results of our experiments, it is sufficient to know the mass and charge of the electron; its dimensions are quite unnecessary. It may well be that electrons actually do not have such a property as size. You cannot, for instance, specify the thickness of the equator, though you can measure its length. Or, maybe, the size of the electron depends upon the conditions of the experiment? Such a possibility also cannot be excluded beforehand. The size of a comet changes as it approaches the sun, even though its mass remains constant. These are not idle questions, and we shall return to them.

ATOMS, ELECTRONS, RAYS

We have just gone over a difficult length in the highroad to knowledge that investigators covered at the close of last century. This was a time when the abundance of new facts and phenomena obscured the simple relations between them. It was a time when only a firm belief in the harmony of nature could keep one from getting lost in the chaos of gay-coloured facts and contradictory hypotheses.

A truly great discovery not only answers old questions, but raises new ones. The discovery of the electron was a source of enthusiasm for physicists all over the world. Soon, however, it was replaced by new troubles. How are electrons bound in the atom? How many are there in the atom? Are they at rest or in motion? And how is their motion related to the radiation of atoms?

The form and the nature of the questions varied, but gradually they reduced to a single problem: it was necessary to find the number, size and arrangement of the electrons in an atom, as well as their influence on the radiation processes.

Nobody gave a thought as to whether such questions make any sense at all. At that time, physicists reticently imagined the electron to be a tiny sphere, 10^{-13} cm in diameter, fixed "somehow" inside the atom, or flying around in some way like a gnat in a cathedral or a typographical period in a cinema palace.

To begin with, the main thing they couldn't understand was why the atom emits spectral lines of a strictly definite wavelength and why there are so many of them (over 300, for instance, only in the visible range of the spectrum for an atom of iron). As always, when no profound ideas are forthcoming, physicists tried to find suitable analogies. They all knew that the frequency of oscillation of a spring to which a small weight is attached depends on its (the spring's) elasticity. Consequently, reasoned one group of physicists, the electrons are held in the atom by "some kind" of springs of various elasticity. When we excite the atom, the electrons begin to oscillate and emit light with the frequencies of the springs. According to Lockyer, it followed that the number of electrons in an atom was equal to the number of lines in the spectrum of the element. Moreover, an atom of such a structure

would more readily absorb exactly those rays which it itself emits. But this is just what Kirchhoff and Bunsen discovered in their famous experiment with sodium vapour.

Notwithstanding the successes enjoyed by the atom model with elastically attached electrons, many physicists understood its logical or, more exactly, aesthetic imperfection. Not much time passed before it was outrightly contradicted by experiments. J. J. Thomson, in investigating the scattering of X rays by the atoms of various elements, came to the conclusion that there were comparatively few electrons in an atom and that their number approximately equals one half of the atomic weight of the element. In 1904, he proposed his atom model (soon to become known as the "plum-pudding atom") based on the hypothesis of his equally famous compatriot William Thomson (Lord Kelvin). This model visualized the atom as having a uniformly distributed positive charge in a sphere about 10^{-8} cm in diameter in which negative electrons, quasi-elastically linked to the atom, float. The number of electrons is equal to the charge of the sphere. Thus, as a whole, the atom is neutral, as it should be.

At the beginning of our century, almost all the physicists accepted Thomson's model; only a very few proposed other models. But, notwithstanding certain conflicting opinions, everybody sensed the onset of a new era in the science of the atom.

ROUND AND ABOUT THE QUANTUM

SPECTRAL ANALYSIS

The discovery of spectral analysis aroused the keen interest even of people who had very little to do with science, which was not a common occurrence

in those days. As always in such cases, for want of a better occupation, rank amateurs searched for other scientists that had allegedly discovered spectral analysis long before Kirchhoff and Bunsen. Among those named were Jean Bernard Léon Foucault (1819-1868), who proposed a similar experiment ten years earlier, the famed astronomer and chemist Sir John Frederick William Herschel (1792-1871), the inventor of photography on paper William Henry Fox Talbot (1800-1877) and many others. The English contended for many years that spectral analysis had been discovered by their famous compatriot George Gabriel Stokes (1819-1903) who had suggested in a conversation with William Thomson (1824-1907) that the D line in the solar spectrum appears in the passage of white solar light through the sodium vapour in the gas blanket of the sun.

With his characteristic unselfishness, Stokes declined such claims, although he admitted that he had expounded similar ideas to his students at his lectures, considering them, however, to be generally known and not especially important. (Incidentally, about this time, Peter Guthrie Tait [1831-1901] had the idea of publishing scientific reviews. He reproved Stokes and William Thomson for their carelessness and ignorance of the literature that had prevented them from publishing an obviously new idea.)

In contrast to their numerous predecessors, Kirchhoff and Bunsen immediately realized the significance of their discovery. They were the first to understand clearly (and could therefore readily convince others) that spectral lines were characteristics of *atoms of a substance* and not features of the structure of the prism or properties of the sun's rays. Kirchhoff immediately began to compile an atlas of the Fraunhofer lines of the solar spectrum and determined the chemical

composition of the sun. He spoiled his eyesight in this work and was forced to abandon it in 1861.

The history and the essence of the discovery of spectral analysis could be the subject of a fascinating narrative. But, unfortunately, this is neither the time nor the place for such a digression. We shall mention only one curious event that took place soon after Kirchhoff and Bunsen's discovery.

On August 18, 1868, during a solar eclipse in India, the French astronomer Pierre Jules César Janssen (1824-1907) observed a yellow line of unknown origin in the spectrum of the solar corona. Two months later, the English physicist Joseph Norman Lockyer (1836-1920) found a way to observe the spectrum of the corona without waiting for an eclipse. He observed the same yellow line in the spectrum. The unknown element by which it was emitted was named "helium", that is the solar element. Both scientists wrote letters describing their discoveries to the French Academy of Sciences. The two letters arrived together and were read at a meeting of the Academy on October 26, 1868. This coincidence amazed the academicians and they decided to have a gold medal coined in commemoration of this event. On one side were the profiles of Janssen and Lockyer, and on the other Apollo in his chariot and the inscription *Analysis of solar protuberances.*

On the earth the element helium was discovered in 1895 by the Scottish chemist William Ramsay (1852-1916).

WILLIAM CROOKES

Sir William Crookes (1832-1919) was born in the family of a tailor in London who had a fairly prosperous shop on Regent Street. He was the eldest of 16 children by his father's second marriage; there were

also 5 by his first marriage. As he himself was wont to say, it was doubtful whether anybody in his family knew the meaning of the word "science". He received his early education from his uncle who had a bookshop next door to his father's shop.

At nineteen years of age, Crookes graduated from the Royal College of Chemistry in London which had been founded not long before he was admitted. Upon graduation, he was appointed junior assistant at this college and continued there until 1854. At the same time, he attended Faraday's lectures at the Royal Institution. They made an unforgettable impression on young Crookes.

In 1861, Crookes discovered the element thallium and in 1869, he was elected to the Royal Society where, on November 30, 1878, he reported to its members on the properties of cathode rays.

It is persistently rumoured that Crookes just missed discovering X rays. The fact is that during his experiments with cathode rays he had continually complained to the Ilford Company that they had supplied him with light-struck photographic plates. (As we now know, the X rays produced when the electrons collided with the walls of the tube could, of course, have fogged the plates, even if they were kept in a lightproof carton.) This rumour has not been confirmed. In any case, Crookes never mentioned it in his speeches or writings.

Crookes was a person with amazingly diverse interests and accomplishments: he was an inventor, the publisher of the journal *Chemical News* and a pure investigator, all at the same time. He was a friendly person, of even temper, devoted to his family and wary of strangers.

"He had a singularly independent, original and courageous mind; he looked at things in his own way and was not afraid of expressing views very different

from those previously considered orthodox." This was noted afterwards of Crookes by J. J. Thomson.

KINETIC THEORY OF GASES

We are engaged now in attempts to penetrate deep into the atom in the company of scientists of the nineteenth century. But along with these attempts, other scientists of the same century tried to explain the physical properties without going into the details of the structure of atoms. The idea underlying these attempts is extremely simple : *atoms, of which all substances in nature consist, are not at rest, but are in continuous motion.*

It was found that such a conception, when properly formulated in mathematical language, led to a great many consequences. Beginning with Newton, who wanted to explain the gas law of Boyle and Mariotte mathematically, such attempts had been made repeatedly. The real founder, however, of the kinetic theory of matter was the Swiss mathematician, Daniel Bernoulli (1700-1782).

Bernoulli was born in a family, originally of Dutch extraction, which has given the world more than 120 distinguished and famous scientists, actors, writers and statesmen. Against the express will of his father, Daniel began his study of mathematics by taking lessons from his elder brother Nikolaus. He continued and completed his education in Italy. In 1725, he and Nikolaus went to Russia and became professors of mathematics in St. Petersburg. The reforms brought about by Peter the Great had attracted many foreign scientists to Russia at that time. Eight months later Nikolaus died of a fever. Daniel lectured in mathematics for seven long years more, as long as he could put up with the Russian climate and way of living in the

first half of the eighteenth century. It was here that he wrote his *Hydrodynamica* which was published in 1738 in Basel, five years after his return.

About this same time, and also in St. Petersburg, similar ideas were being developed by Mikhail Vasilyevich Lomonosov.

Strange was the fate of the kinetic theory of gases. No notice was taken of Bernoulli's *Hydrodynamica* and it came to light again only 120 years later, in 1859, while Lomonosov's work, written in the years 1742-47, became known only in 1904.

The kinetic theory of gases was born for the second time in the nineteenth century. At first, it did not achieve much success, as before. In 1821, John Herapath (1790-1868), a spirited and disputatious schoolmaster of Bristol, again proposed the kinetic hypothesis, and again it was disregarded. A quarter of a century later, in 1845, John James Waterston (1811-1883), a naval instructor in Bombay to the cadets of the East India Company, submitted a very long paper on the kinetic theory of gases to the Royal Society in London. This work was not published since one of its reviewers assessed it as "nothing but nonsense, unfit even for reading before the Society". It was only in 1892 that Lord Rayleigh found Waterston's manuscript in the archives and had it published.

The cause of such a unanimous unmindfulness of these works is evidently a result of the general frame of mind of the physicists of that day. This was due, in part, to the philosophical teachings of that time. In the middle of the nineteenth century, almost all philosophers denied the existence of atoms. (This is quite strange since the philosophers of the eighteenth century considered the existence of atoms to be an obvious fact and even a trivial one.)

Nevertheless, the ideas of Herapath and Waterston

were not lost; they had a decisive influence on the work of James Prescott Joule (1818-1889), an English brewer of Salford with physics for a hobby. In 1851, he first estimated the velocity of a gas molecule. It turned out to be unexpectedly high. The velocity of a molecule of hydrogen, for example, is about 1800 metres per second, twice that of a gun shell.

Further development of the kinetic theory of matter took place at a much more rapid pace. It was rediscovered in 1856 by August Karl Krönig (1822-1879) and in 1857 by Rudolf Julius Emanuel Clausius (1822-1888). Then it was developed almost to its present state in 1860 by James Clerk Maxwell and by Boltzmann in 1878. It seemed that now the atomic hypothesis had finally won a decisive victory.

But as soon as ten years later it "went out of fashion" again. Boltzmann's works aroused "more astonishment than recognition" and he was called "the last foothold of atomism". He himself sadly admitted, "I am the last who denies the possibility of constructing any other picture of the world except the atomic one". This new wave of disbelief penetrated into textbooks and scientific papers. For example, one of the well-known textbooks of the time wrote in 1885 that "the solid atom is still alive (in the form of an incredible but not yet disproved hypothesis).... Incomparably more plausible is the theory that matter is continuous, that is that it does not consist of particles with spaces between them". Even as late as 1898, one of the scientific journals wrote that "... the kinetic theory is just as wrong as the mechanical theory of gravitation".

However, the avalanche of discoveries at the beginning of the twentieth century completely swept away these belated doubts and, from then on, the kinetic theory of matter has been one of the principal sciences dealing with the structure of substances. It has been

used to explain the specific heat and thermal conductivity of solids, the elasticity, viscosity and diffusion of gases and many, many more phenomena.

MIKHAIL VASILYEVICH LOMONOSOV

The first Russian scientist Mikhail Vasilyevich Lomonosov was born on November 8, 1711, in the distant northern village of Denisovka on one of the islands in the Northern Dvina River near the town of Kholmogory. In the winter of 1731, when he was twenty years of age, he came on foot with a string of loaded wagons to Moscow where he began his education. He died on April 4, 1765, a member of the Russian Academy of Sciences and an honourable member of the academies of Stockholm and Bologna.

Everything about Lomonosov is amazing: his powerful constitution, his wide range of interests and his extraordinary creative genius. He was the first to read his scientific lectures in the Russian language. This required a new Russian scientific terminology and he established one. He wrote the first Russian textbook on mineralogy and laid the foundation for modern Russian poetics; he supervised the mapping of Russia and wrote a work called "On the Propagation and Preservation of the Russian People", he made mosaics out of bits of coloured glass he had himself produced by a new method and fitted out an expedition to search for a sea passage to India along the northern coast of Russia; he designed navigational instruments and built the first chemical laboratory in Russia.

In 1755, the first Russian university was founded in Moscow with the active participation of Lomonosov. Later it was named after him.

The scientific views of Lomonosov were on the level of his century and, in many cases, far in advance. He

was a consistent supporter of atomism and as relentless an opponent of the phlogiston theory. Forty years before Lavoisier he systematically used scales in chemical investigations, he conducted the famous experiment with the heating of metals in sealed retorts seventeen years before Lavoisier, and discovered the atmosphere of Venus 30 years before Sir William Herschel.

Lomonosov endured many hardships. Russia at that time was a feudal illiterate country and the pursuit of scientific knowledge was not considered an honourable one. Lomonosov was obliged to look for patrons at court, and to waste his time on a multitude of affairs having nothing to do with science. But he inspired his students with the thought that "nothing can be more pleasant and useful for posterity than physico-chemical experiments conducted in spare time, free of more important matters".

Because his work has become known only in this century, and because many of his ideas are startingly modern, we shall make special mention of the contribution of Lomonosov to the science of atoms and their motion. In 1742, in a dissertation called *On the Tiny Imperceptible Physical Particles, Constituting All Bodies of Nature, in Which Are Inherent Properties Sufficient to Account for Specific Phenomena*, he wrote:

"§ 87. Axiom. Complex bodies comprise a certain number of component parts into which they decompose....

"§ 89. Theorem 10. All bodies comprise tiny imperceptible physical particles in which properties are inherent and which cannot divide in motion into other smaller particles....

"§ 90. Explication. We call tiny imperceptible physical particles, which do not divide into other, smaller

ones in motion, physical monads. We do not disclaim the possibility of dividing matter in thought to infinity, but believe it possible, without fear of erring, to do without such division in physical matters. Likewise, we do not concern ourselves with the void dispersed throughout matter (if such exists). No conception is linked to this void except that of extent. Therefore, it has no properties and thereby can give no essence to the nature of things, irrespective of whether it exists or not.

"§ 91. Theorem 11. The shape of the physical monad is immutable...."

The cause of heat and cold Lomonosov perceived to be "in the mutual movements of tiny imperceptible particles". In 1744, he submitted to the Russian Academy of Sciences a dissertation called *Reflections on the Cause of Heat and Cold.* You can get an idea of this paper from the following extracts.

"§ 1. It is well known that heat is evoked by motion: your hands become warm when you rub them together, wood catches fire, sparks fly when you strike flint on steel, iron is heated if you forge it with quick, heavy blows....

"From these examples it is quite evident that there is sufficient reasons to consider that heat consists in the motion of any kind of matter....

"§ 6. Internal movements can be conceived of taking place threefold: (1) either the tiny imperceptible particles of a body are continuously moving from place to place, (2) or they continuously revolve in one place, (3) or, finally, they continuously oscillate, back and forth, in imperceptible space during imperceptible time. The first we call translatory, the second rotative and the third oscillatory motion...."

A review of this paper, recorded in the transactions of the Academy, says that "Junior Assistant Lomono-

sov has begun to compose dissertations too soon". The comparatively low cultural level of the Academy of Sciences in the eighteenth century and the subsequently increasing isolation of Russia from western Europe brought about a situation in which Lomonosov's works, many from fifty to a hundred years ahead of his time, had no influence on the subsequent development of science. They were forgotten and, in the memory of posterity, he remained only a great poet for the next century and a half. Only later, in preparing for the 200th anniversary of his birth, Lomonosov's scientific works were extracted, one by one, from the archives, and everyone understood the true greatness of this verily Russian man of talent.

Chapter Three

ATOMS * RAYS * QUANTA * COMPLETE VICTORY OF ATOMIC THEORY

They say that man acquires half of his knowledge of the surrounding world before he is five years old. By the next ten years he knows almost everything about the world, and his subsequent knowledge (except, perhaps, for special branches) is enlarged very slowly. This may be because he has already fallen into the baneful grown-up habit of not failing to ask: "And what is it for?" when he finds out some new fact.

In one's first acquaintance with quantum mechanics, this grown-up habit is a great hindrance because, at first, neither the essence of atomic phenomena is clear, nor their relative significance in the general picture, nor, especially, their hidden meaning.

It may be expedient, in this situation, to act as children learning to speak. First they hear sounds that they don't understand, then they meaninglessly recall and repeat words and, finally, they notice that there are logical connections between them. Gradually they find that words frequently have no meaning in themselves, but sometimes acquire an unexpected significance when they are spoken in a definite order.

A long time passes, of course, before they are able to catch the most subtle shades of meaning and moods concealed in simple combinations of everyday words. It is only then, actually, that they become grown-ups.

In this chapter we shall learn many new facts about atoms, rays and quanta. Maybe our choice of these facts and the certitude with which we shall interpret them will not seem to be too well-founded at first, just as the actions of an adult seem to a child. But this cannot be helped. In first perceiving the uncustomary reality of atomic physics, we willy-nilly become like children entering a new world. There is no science without facts. To master them better, let us become children for a time; they always know more than they can understand.

The end of last century and the beginning of the present one are often called the heroic era of physics. This was a time when each year introduced new and unexpected discoveries whose fundamental character is obvious even now, more than half a century later. One such discovery was connected with the same Crookes' tube. On November 2, 1895, in his university laboratory in Würzburg, Wilhelm Konrad Röntgen (1845-1923), when investigating cathode rays, discovered a new kind of radiation that came from the point on the anode struck by the beam of electrons.

The properties of this radiation were unusual, frighteningly unusual: it readily passed through the human body and could even penetrate through the closed door of a steel safe. It was only in 1912 that Max Theodor Felix von Laue (1879-1960) suggested to his associates, the German physicists Walter Friedrich (born 1883) and Paul Knipping (1883-1935), that they try passing these rays through crystals. They found them capable of both interference and diffraction. This meant that

X rays (as Röntgen had named them from the start) are not a beam of particles, but are waves, though of extremely short wavelength: from 10^{-7} to 10^{-10} cm.

This discovery alone would have been sufficient to upset the customary routine of physical laboratories all over the world. But the era of discovery had only begun. Only several months passed when, in 1896, Antoine Henri Becquerel (1852-1908) discovered an even stranger kind of radiation. It was produced spontaneously in a piece of uranium ore and consisted of positively charged particles which Rutherford named alpha (α) particles. They turned out to be four times as heavy as atoms of hydrogen, and their charge equal to two charges of an electron.

Certain substances (for example, ZnS—zinc sulfide) produce tiny flashes of light when they are struck by a beam of α particles. This enabled William Crookes to display his inventive genius again by devising the spinthariscope in 1903. This instrument, more commonly known as a scintillation counter, permits the flashes to be seen when single alpha particles strike the zinc sulfide screen.

These two discoveries are well known now, but we have mentioned them, nevertheless, because the history of the atom would be incomplete without them.

ATOMS

A great variety of conceptions, some quite fantastic, of the structure of the atom were current in physics at the beginning of the present century. Karl Louis Ferdinand von Lindemann (1852-1939), Rector of the University of Munich, contended in 1905 that "... an atom of oxygen has the shape of a ring, and an atom of sulphur, the shape of a cookie". Still alive was Lord Kelvin's theory of the "vortex atom", according to

which the atom is similar to a smoke ring blown by a skilled smoker (Incidentally, Kirchhoff said that "this is an excellent theory because it excludes all others".)

Most physicists, however, agreed with J. J. Thomson that an atom is a uniformly distributed positive charge in a sphere approximately 10^{-8} cm in diameter in which are embedded negative electrons (or corpuscles, as they were called in the early nineteenth century) of a size equal to about 10^{-13} cm.

But J. J. himself (as he was called by his assistants), showed no especial enthusiasm for his model. There were certain physicists that had an entirely different conception of the atom.

Some of them spoke aloud of their dissent. One of these, George Johnstone Stoney, surmised as far back as 1891 that the electrons move around within an atom like the satellites of planets. Another, Jean Baptiste Perrin, tried in 1901 to picture the "nuclear-planetary structure of the atom". A Japanese physicist, Hantaro Nagaoka (1865-1950) contended in 1902 that the space inside an atom is extremely huge in comparison to the electric grains or, in other words, that the atom is, in its way, a complex astronomical system, similar to the rings of Saturn. Many scientists agreed with these statements. Among them were Sir Oliver Joseph Lodge, the French physicist Paul Langevin and the Norwegian scientist Carl Anton Bjerknes (1825-1903). This list could easily be continued. Suffice it to mention that the planetary structure of the atom had been used as far back as 1896 by Lorentz and Larmor to explain Zeeman's discovery of the splitting of spectral lines in a magnetic field.

Other scientists, for instance, Pyotr Nikolayevich Lebedev, the Russian physicist who first proved the existence of light pressure, entrusted his ideas on this

subject only to his diary. In 1887, it seemed to him that the frequency of radiation of atoms is determined by the frequency with which electrons revolve on their orbits. The voice of another Russian scientist, Nikolai Alexandrovich Morozov (1854-1946), was silenced by the walls of the tsarist dungeon in the Schlüsselburg Fortress in which he was imprisoned for 21 years.

But not a single advocate of the planetary atom could explain the main point: the stability of a system consisting of a positive core about which electrons revolve.

In fact, an electron travels with accelerated motion on a circular orbit and therefore, according to the Maxwell-Lorentz theory, it should lose energy by radiation. Knowing the size of the atom, we can readily estimate the velocity of the electron travelling on its orbit $v \approx 2 \times 10^8$ cm/s and the centripetal acceleration $a \approx 10^{25}$ cm/s^2. With such an acceleration, the radiation must be so intensive that within 10^{-11} s the electron must fall into the positive centre of attraction and the "atom" cease its existence.

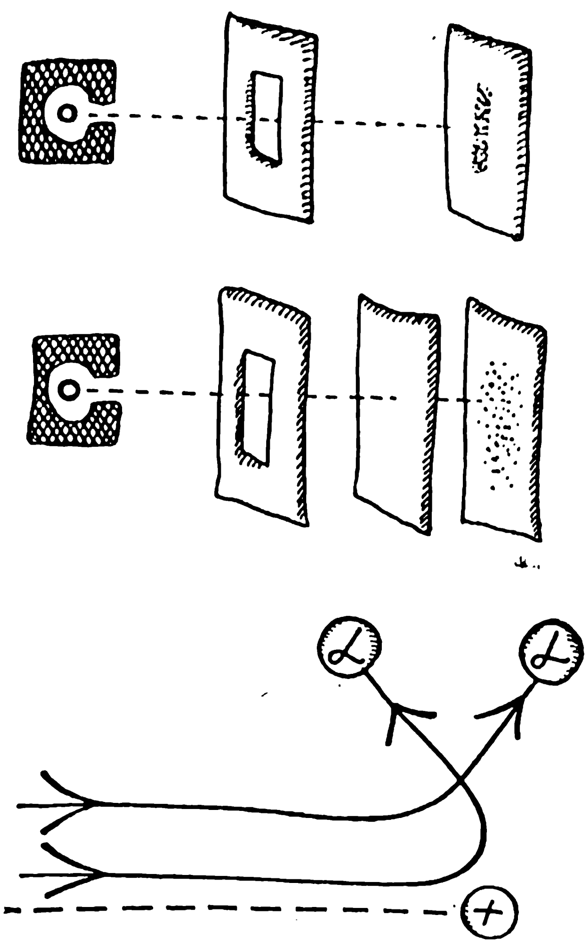
But nothing like this ever really happens in nature; the atom is not only stable, its structure is restored after being destroyed. On the face of it all this speaks in favour of the Thomson model. A rule, however, adopted over two hundred years ago, states that only experiment has the right to make a final choice between conflicting hypotheses. Such an experiment was conducted in 1909 by the New Zealand-born physicist, Ernest Rutherford (1871-1937) and his "boys".

Imagine a large and noisy man who is obliged to sit for long weary hours in a dark room and, looking into a low-power microscope, count the tiny flashes of light, called scintillations (from the Latin word *scintilla* meaning a spark) produced on the screen of a spinthariscope when struck by alpha particles. This work was

excruciating and the eyes tired after only two minutes of observation. Rutherford's assistants in these experiments were the experienced investigator Hans Geiger (1882-1945) and a twenty-year-old laboratory technician Ernest Marsden (1889-1970). Their apparatus was not complicated. It consisted of a vial containing radium-C, which emits alpha particles, a diaphragm which confines these particles to a narrow beam and directs them onto a zinc sulfide screen and a microscope for observing the scintillations of the alpha particles on the screen. Though it is impossible to predict the spot on the screen where the next scintillation will appear, since they are produced at random, still, quite a sharply defined image of the diaphragm slit is obtained as a whole on the screen.

Now, if we place a piece of metal foil in the path of the alpha particles, we will obtain a blurred band on the screen instead of the clear-cut image of the slit. This band is only slightly wider than the slit image obtained before: the alpha particles have been deflected only by two degrees. A fairly simple calculation showed, however, that to explain even such a small deflection it was necessary to assume that enormously powerful electric fields with intensities exceeding 200,000 V/cm can be developed in the atoms of the foil.

There can be no such intensities in the positive sphere of the Thomson atom. Collisions with electrons can be disregarded: in comparison with them an alpha particle, travelling with a velocity of 20 kilometres per second, is like a cannon ball alongside some peas. Still, the paths of the alpha particles were bent by something. In his search for an answer to this puzzle, Rutherford proposed to Marsden (later Sir Ernest), that they check whether any of the alpha particles can be reflected from the foil and turned back toward



the source. From the viewpoint of Thomson's model, the suggestion was absolute nonsense: a cannon ball cannot be reflected by a pea. The result was unexpected but quite convincing, though hard to believe. The alpha particles were turned back by the foil.

Two years passed. During this time Geiger and Marsden had counted over a million scintillations and had proved that approximately one alpha particle in 8,000 is thrown almost backward toward the source.

Only then, on March 7, 1911, Rutherford read his historical paper "The Scattering of α and β Particles by Matter and the Structure of the Atom" before the Manchester Literary and Philosophical Society whose president John Dalton had once been. That day the audience heard that an atom resembles the solar system, consisting of a nucleus and electrons revolving

about it at distances of $\approx 10^{-8}$ cm. The size of the nucleus is very small, only 10^{-13} or 10^{-12} cm, but in it is confined practically all of the mass of the atom. The nucleus has a positive charge equal in magnitude to about one half of the atomic weight of the element. The comparison with the solar system is no mere chance: the size of the solar system (6×10^9 km) is about the same number of times larger than the diameter of the sun (1.4×10^6 km) as an atom ($\approx 10^{-8}$ cm) is larger than the diameter of a nucleus ($\approx 10^{-12}$ cm).

We have become so used to the new concepts that in explaining electronics we refer to a TV set, and in speaking of mechanics we bring in the steam locomotive as an example. For this reason, it is difficult for us now to understand the perplexity of scientists of the same calibre as Rutherford. Everything is so clear to us now: alpha particles are simply deflected by the nuclei of atoms. This is a picture we have been accustomed to from childhood. But it took exceptional scientific courage, gained through extensive labour and based on precise knowledge, to draw this picture for the first time. Before this picture became known to everybody, not only over a million scintillations had to be counted. It was necessary (as Geiger recalled many years later) to overcome enormous difficulties whose purpose we are now unable to understand. First it took ten years (!) to prove that alpha particles are none other than helium atoms that have lost two electrons. This proof was far from simple and this was understood by the Swedish Academy of Sciences when in 1908 it awarded Rutherford a Nobel Prize for his investigation in the chemistry of radioactive substances, as a result of whose disintegration alpha particles are formed. All the painstaking labour and sleepless nights were gradually forgotten. The result was more important and simpler than the way that led to it.

Physicists took Rutherford's report reticently. For the next two years he himself did not insist very strongly on his model, though he was very sure of the unerring experiments that had led to it. The reason was the same as before. If we are to believe in electrodynamics, such a system cannot exist because, according to its laws, a revolving electron must inevitably and rapidly fall into the nucleus. One had to choose: either electrodynamics or the planetary atom. Physicists silently chose the former. Silently, because Rutherford's experiments could neither be forgotten nor disproved. Physics had run into a blind alley. There had to be a Niels Bohr to find the way out again.

RAYS

Independently of the hypotheses concerning the structure of atoms, scientists realized early in the game that some knowledge of the atom can be obtained by studying its line spectrum (just as a musician can determine the length of a string by its tone, and can recognize a musical instrument by its chord). In physics any investigation is reduced eventually to measurement. Hence it was necessary first of all to learn to measure the length of waves as accurately as possible, that is, to study the structure of the line spectrum even more intently than Fraunhofer did.

This could not be done with the prism spectrograph of Kirchhoff and Bunsen. The glass prism was replaced by a diffraction grating which was considerably improved by Henry Augustus Rowland (1848-1901), a representative of the then still young school of American physicists.

With the aid of this instrument, tens of thousands of spectral lines of various elements were measured in the following decades by Carl David Tolmé Runge

(1856-1927), Heinrich Gustav Johannes Kayser (1853-1940) and especially in the laboratory of Friedrich Paschen (1865-1940) in Tübingen. These data were carefully listed in long tables. By 1913, the total number of works on spectral analysis had already exceeded 50 thousand. In particular, it was found that the famous yellow D line in the spectrum of soda was actually two very closely spaced lines: $D_1 = 5895.9236$ Å and $D_2 = 5889.9504$ Å. (The length 1 Å $= 10^{-8}$ cm, i.e. approximately the diameter of an atom.)

The supreme aim of any science is not to accumulate facts, but to establish relationships between phenomena and to find their cause. It was clear to anybody that these long tables contained a huge amount of information on the structure of atoms. But how to extract it? (Probably, Egyptologists, prior to Champollion, had the same feeling when they tried to read hieroglyphics.)

The first step is always difficult and inconspicuous. Hence we know very little about Johann Jakob Balmer (1825-1898) who first discovered some sort of system in this chaos of numbers. We know that he was born in the town of Lausen in the Swiss canton of Basel on May 1, 1825. He graduated from secondary school in this town and then went on to study mathematics in the universities of Karlsruhe, Berlin and Basel. He obtained his Ph.D. in mathematics in 1869 and became a Privatdocent at the Basel University. He soon left the university, however, to teach physics at a girls' secondary school. He was already 60 when he suddenly noticed that the four spectral lines in the visible range of the hydrogen spectrum are not arranged at random, but form a *series* which can be described by a single equation:

$$\lambda = b\frac{k^2}{k^2 - n^2}$$

where $n=2$, $k=3, 4, 5, 6, \ldots$ and $b=3645.6$ Å.

This simple relationship deserves great attention. The fact is that it is *exact*, as anyone can see for himself.

Just take a look at the following table which was drawn up by Balmer in 1885:

Calculated by Balmer	Measured by Ångstrom	n	k
6562.08	6562.1	2	3
4860.80	4860.74	2	4
4340.0	4340.1	2	5
4101.3	4101.2	2	6

The first column lists the wavelengths of the first four spectral lines as calculated by Balmer's formula, the second column lists the same wavelengths as measured shortly before with great precision by the Swedish physicist Anders Jöns Ångstrom (1814-1874). The coincidence of the measured and calculated values is amazing. Such coincidences cannot happen by chance and, consequently, Balmer's discovery was not lost in the archives, but led to a whole chain of new investigations.

Sometimes Balmer is portrayed as a somewhat eccentric schoolmaster who could find nothing better to do than divide and multiply various numbers until he accidentally came across a simple relationship between them. This is quite incorrect. He was a well educated man of profound knowledge; he wrote papers on various problems of projective geometry and continually returned to the most complex problems of the theory of cognition. For instance, in 1868, he published a paper in which he tried to establish the relation

between scientific researches and systems of world philosophy. From childhood he had been under the influence of the Pythagoreans with their teachings of harmony and the mystic role played by whole numbers in nature. Like the ancients, Balmer was convinced that the mystery of the unity of all observed phenomena should be sought for in various combinations of whole numbers. Hence, when his attention was drawn by the sets of clearly defined spectral lines, he approached this phenomenon of nature with his own biased measure. His expectations were not disappointed: the wavelengths of spectral lines really did turn out to be related by a simple rational equation.

Balmer's discovery opened a whole new era in the science of the atom. In essence, the whole theory of the atom begins with his formula. Though no one knew this at the time, many physicists had probably already sensed something of the kind. Even before another year had passed, in 1886, Runge noticed that Balmer's formula becomes more obvious if the

frequency $\nu = \frac{c}{\lambda}$ is substituted for the wavelength λ.

Thus

$$\nu = \frac{4c}{b}\left(\frac{1}{4} - \frac{1}{k^2}\right)$$

In 1890, the Swedish physicist, Johannes Robert Rydberg (1854-1919) proposed that the formula be written in the form used today:

$$\nu = cR\left(\frac{1}{n^2} - \frac{1}{k^2}\right)$$

where c is the velocity of light, n and k are the arbitrary familiar whole numbers and the number $R = 109{,}677.5937\ \mathrm{cm}^{-1}$ was named the Rydberg constant for the hydrogen atom. Assuming in this formula that $n=2$, we can calculate the whole Balmer series which was subsequently measured to a value of $k=31$.

The idea of writing the frequency ν as the difference of two spectral terms T_n and T_κ appeared at the same time. Thus

$$\nu = \frac{cR}{n^2} - \frac{cR}{k^2} = T_n - T_k$$

So far there seemed to be no point or particular advantages in such a notation. In 1908, however, the young Swiss scientist Walter Ritz (1878-1909) explained its benefits. Continuing the work of Rydberg, he formulated the so-called *combination principle*: the frequency ν of an arbitrary line in the spectrum of any atom can be represented as the difference of two spectral terms T_n and T_k. Thus

$$\nu_{nk} = T_n - T_k$$

even in the case when a separate term T_n cannot be expressed in such a simple form as for an atom of hydrogen.

At first glance, this promises no particular gain: from a set of frequencies we have simply changed over to a set of terms. This is not so, however. Just attempt to read a book in which there are no spaces between the words, and you will sense the difference immediately. Especially if the book is in a foreign language. Moreover, there were much fewer numbers to deal with: to determine the frequencies of 50 lines of hydrogen, known at the beginning of this century, some ten terms were sufficient.

Suddenly, a system was discovered in the chaos of numbers. The confused set of lines broke down into series. They began to distinguish separate words in the unintelligible book. In the simplest case—that of the hydrogen atom—it became possible even to make out the letters of which the words are constructed. The meaning of the words and the origin of the letters, however, remained as much a mystery as before: the hieroglyphics had not yet spoken, though they did not seem so puzzling any more.

The effort to understand the meaning of the structure of spectra really did remind one of an attempt to decipher (almost blindly) an unknown text. This wearisome work dragged along for over a quarter of a centu-

ry, and the lack of a general guiding idea kept away some of the greatest scientific minds of the century. It was necessary to find the key to the cipher.

This was done by Niels Bohr in 1913.

QUANTA

Radiation originates inside an atom but, once having left the atom, exists independently. Sometimes it is made up of waves of the same length; such radiation is said to be monochromatic. The line spectrum of an atom consists of a set of monochromatic rays, and these sets differ for different atoms.

Up till now we have been concerned mainly with only one feature of waves: their frequency ν. Rays, however, are complex phenomena, and their properties cannot be reduced only to the frequency of radiation. A sunbeam is transparent but quite material, it even has weight: each minute 2×10^{-15} grams of light fall on each square centimetre of the earth's surface. Not at all appreciable it would seem, but this means that 80 thousand tons of sun rays fall on our planet annually. These tons of rays accomplish the circulation of substances in nature, so, in the final analysis, all life on earth is possible only under the sun.

The action of radiation can best be pictured as ocean waves running up on the beach. After the work of the Dutch physicist Christiaan Huygens (1629-1695) and the French physicist Augustin Jean Fresnel (1788-1827) such an analogy became indisputable. Each year brought new proofs in the phenomena of interference and diffraction of light. In 1873, James Clerk Maxwell (1831-1879) theoretically predicted that light, falling on the surfaces of bodies, should exert a pressure on them (also fully in agreement with our analogy). Light pressure is a very fine effect, but Pyotr

Nikolaevich Lebedev (1866-1912) observed it experimentally, nevertheless, in 1899. It seemed that the wave nature of light had been proved so reliably that any further experiments in this line would be senseless.

Fortunately, experiments are conducted in physics not only to test theories. At the same time that Lebedev was concluding his famous experiment, another experiment, just as painstakingly accurate but more incomprehensible, was being conducted. In 1887, Heinrich Rudolf Hertz (1857-1894) (the same physicist that proved the wave nature of electromagnetic radiation and, thereby, the validity of the whole electrodynamics of Maxwell) discovered a phenomenon which was later named the *photoelectric effect*. Its essence is as follows.

If the light of a mercury-discharge lamp (called a quartz lamp now) is directed on metallic sodium, electrons will be emitted from the surface of the metal.

By the end of the century, the majority of physicists were fully aware that the atom was of a complex structure and, therefore, by itself this phenomenon did not astonish anybody. Quite soon, all the physicists agreed that the electrons in Hertz' experiment were ejected from the atoms of sodium due to the radiation of the quartz lamp.

What were strange and incomprehensible were the *laws* of this phenomenon. They were established by the German physicist Philipp Eduard Anton Lenard (1862-1947) and the Russian physicist Alexander Grigoryevich Stoletov (1839-1896) just before the end of the century. These scientists measured the quantity and *velocity* of the emitted electrons as functions of the *intensity* and *frequency* of the incident radiation.

We already know that rays originating inside atoms

differ from one another both in their wavelength λ (or, what is the same, the frequency ν) and their intensity. This is readily evident from spectrograms in which certain lines are considerably brighter than others. For instance, in the yellow doublet of sodium, the D_2 line is twice as bright as the D_1 line.

Our previous experience and knowledge of waves tell us that the action of waves will be the more appreciable, the greater their amplitude. A visit to the seashore during a storm at sea will quickly convince us of this. Consequently, by increasing the amplitude we also increase the intensity of rays. The intensity of radiation can be increased in another way as well: by increasing the number of radiating atoms. Therefore, if, instead of one mercury-discharge lamp, we take two, three, or ten, the intensity of radiation will increase the same number of times. It is natural to expect that the energy of the emitted electrons will grow in the same proportion.

But the energy of the electrons remained at the previous value, only their quantity increased.

This was the first incongruity in store for the scientists at the end of their experiments. In return, the energy was found to depend on the frequency of the incident radiation, and to no small degree.

A quartz lamp emits violet and ultraviolet rays. If, instead, a beam of red rays is directed onto the surface of the sodium, no electrons whatsoever will be emitted no matter how many lamps we use.

"If radiation is a wave process (which has been rigorously proved), this cannot happen," contended one group of physicists.

"But it does!" argued another group.

If a large cliff jutting into the sea were to collapse suddenly before your eyes, you would probably look for the external causes of this unforeseen occurrence.

Of course, the waves of the sea gradually wash out and undermine the shore, and cliffs collapse from time to time, but everybody knows how rarely this occurs. But, if you hear the report of heavy guns and, turning, see a warship offshore firing away at the cliff with salvos from its main armament, you immediately guess that the unexpected destruction was caused by the shells rather than by waves, although their energy is less than the total energy of sea waves. The energy of waves is uniformly distributed, however, along the seashore, and centuries are required for the results of their daily efforts to become evident. In comparison with the work performed by waves, the energy of a shell is negligible, but it is concentrated in a small volume and is released instantaneously. If, in addition, the shell is of sufficiently large gauge, it will demolish the cliff. This last is especially important. As a matter of fact, all the properties of a gun shell, except its size, are possessed by a rifle bullet which, however, cannot shatter a cliff.

This, approximately, is the line of reasoning followed by Albert Einstein when he proposed his explanation of the photoelectric effect. He knew of Planck's discovery, but for him, with his unbiassed manner of thinking, the hypothesis of quanta of light did not seem so terrible as it did to Planck. Therefore, Einstein was the first who not only believed in it, but applied it for explaining new experiments. Einstein maintained that not only was light emitted in quanta, as required by Planck's hypothesis, but was also *propagated* in quanta. Hence light falling on the surface of the metal is similar to shells rather than to sea waves. Moreover, each such shell-quantum can release only one electron from the atom.

According to Planck (remember Chapter One), the energy of a shell-quantum equals $h\nu$. Einstein figured

that some portion of this energy, let us call it P, is expended to eject the electron from the atom, and the rest to accelerate it to the velocity v, i.e. to impart the kinetic energy $\frac{mv^2}{2}$ to it. These two statements can be concisely expressed in the form of a simple equation

$$h\nu = P + \frac{mv^2}{2}$$

Once we accept this hypothesis, the phenomenon of the photoelectric effect begins to clear up. Indeed, while the size of the shells is small (red light), they cannot eject an electron from the atom ($h\nu < P$), no matter how many we fire. If we begin to increase their size (violet light), their energy finally becomes sufficient to eject electrons ($h\nu > P$). But, as before, the energy of the shell-quanta will depend only on their size (that is, on their frequency ν), and not on their quantity.

Sixteen years later, the Swedish Academy of Sciences awarded the profound simplicity of Einstein's equation with a Nobel Prize. But in 1905, when the equation was first written down, everybody attacked it, even Planck. He was fond of Einstein and therefore, in persuading the Prussian Ministry of Education to invite him to teach in Berlin, he asked that Einstein "should not be reproached too strongly" for his hypothesis concerning the photoelectric effect.

One can understand Planck's feelings about this matter: he had just introduced the quantum of action h despite generally accepted tradition and his own desire. Only gradually did he become conscious of the inevitability of this step. Even as late as 1909, he confessed to Einstein: "I still don't believe very strongly in the reality of light quanta."

However, the mischief had been done. "... Planck

planted a flea in the ears of physicists," Einstein said twenty years later, and it gave them no peace, even when they tried to take no notice of it. At any rate, Planck tried to introduce his quantum of action so as not to do any damage to wave optics which was an edifice of exceptional beauty that had been built, stone by stone, for two centuries. For this reason, according to Planck, light was only emitted in quanta, but was propagated, as before, as a wave. Only in this way could all the results of wave optics be saved.

Einstein, on the other hand, acted as if no physics had existed before he came on the scene or, at any rate, as a person having no knowledge of the true nature of light. In this he displayed one of his most remarkable features: he was able to use logics to perfection, but he had more trust in his intuition and in facts. For him there were no accidental facts in physics. Hence, in the phenomenon of the photoelectric effect he sensed a signal of nature indicating the existence of as yet unknown, but profound laws rather than an annoying exception to the rules of wave optics.

It just happened that historically it was the wave properties of light that were studied first. It was only in the photoelectric effect that physicists first ran into its corpuscular properties. The inertia of thinking of the majority of them was so great that they refused to believe what they observed. "This is quite impossible!" they exclaimed, like the farmer who saw a giraffe for the first time in his life.

Einstein, of course, was acquainted with the history of optics as well as anybody else. But his independent mind treated its indisputable prestige with indifference. He attached no importance to all the past services of optics if it could not explain a single, but undeniable, experiment. He profoundly, almost religiously, believed in the unity of nature, and for him one such

experiment signified no less than the entire history of optics. His honesty would not allow him to disregard a single disagreeable fact.

Only incorrect experiments are really dangerous to science; it is customary to believe experiments. And any hypothesis, no matter how attractive, is always carefully tested. Even if it turns out to be wrong, the experiments that disproved it often lead to results more valuable than the hypothesis itself. Einstein's hypothesis was also tested; it turned out to be true.

In 1911, in checking the validity of Einstein's equation, Robert Andrews Millikan (1868-1953) used it to determine the value of Planck's constant h. It coincided with the value obtained by Planck from the theory of thermal radiation. Soon an experiment was conducted whose principle was exactly similar to the picture of the cliffs collapsing on the seashore. Again Einstein was right and not the recognized authority of wave optics.

To be sure, Einstein did not deny that wave optics existed. Nor did he dispute the experiments proving the wave nature of light. He simply brought the contradiction that arose to its logical conclusion and left it to be settled by the next generation of physicists. Moreover, as early as 1909, in addressing the 81st meeting of the Physical Society in Salzburg, he foresaw that "the next phase of development in theoretical physics will provide us with a theory of light which will in some sense be a blending of the wave theory of light with the emission theory". Twenty years later, his prediction came true.

Notwithstanding the unanimous objections to it, the idea of quanta of light did not perish, and eight years later it sprouted into powerful shoots. This happened in 1913 when a shy and unhurried Dane, Niels Bohr, came to work in Rutherford's laboratory.

COMPLETE VICTORY OF ATOMIC THEORY

With a solemnity obligatory to true English tradition and appropriate to the significance of the event, the centennial of the atomic theory of matter was duly celebrated on May 20, 1904, in Manchester where John Dalton had spent the most fruitful years of his scientific work.

The victory of this theory was not an easy one. Even after Dalton's investigations, many physicists regarded atomic theory simply as a "curious hypothesis, permissible from the viewpoint of our cognition". The unanimity with which the philosophers of last century denied the existence of atoms shook the belief of physicists in them as well. For instance, the Austrian philosopher and physicist, Ernst Mach (1838-1916) called all advocates of the atomic theory "a congregation of the faithful" and would interrupt anyone who tried to convert him to this belief with the question "Have you ever seen one yourself?" Only in 1910, when he first saw the scintillations of alpha particles on the screen of a scintilloscope he admitted with reserve and dignity, "Now I believe in the existence of atoms". Mach can be understood: it is difficult for a person to conceive of anything beyond that which is indivisible *in principle*. Nevertheless, the idea of the atom won a final and decisive victory at the turn of the century. Reason proved to be capable of understanding even that which it was unable to conceive. This came about much sooner than the 300 years predicted by Ludwig Eduard Boltzmann (1844-1906) who died tragically in solitude, not understood by his contemporaries.

Still, the victory did come a little too late. After the work of Thomson and Rutherford, the concept of the "atom" lost its previous meaning. It became clear

that the atom was not the simplest particle of matter, even though it could not be split up by chemical means. "Unfortunately, the laws of nature become entirely clear only when they are no longer correct," said Einstein. This does not mean, of course, that the laws lose their significance at the same time. In the history of the atom, notwithstanding further advances in science, proofs of its reality (even in the sense of the ancient Greek the term *atomos*, meaning "indivisible") will always be among the most important achievements.

In exactly the same way as we continue to speak of the rising and setting of the sun, we speak of atoms implying something entirely different from what the ancient Greeks conceived.

The final substantiation of atomism, as the atomic theory can be called, is also connected with Einstein who, independently of the Polish physicist Marian Smoluchowski (1872-1917), worked out the exact mathematical theory of Brownian motion. His theory was confirmed experimentally by Jean Baptiste Perrin who, on the advice of Langevin, undertook a systematic and thorough investigation of Brownian motion in 1909. Many physicists had been convinced even before Perrin that the true cause of this motion was the bombarding of the particles by molecules of the liquid, which were invisible even in the most powerful microscope. But the amazingly elegant experiments of Perrin not only proved the correctness of this assertion, but led to something more important: this incomprehensible motion of particles in a liquid was an exact *model* of the true motion of invisible molecules, magnified several thousand times. Hence, when we study the Brownian motion of particles, we obtain a graphical picture of the motion of invisible molecules. (Exactly in the same way that a knowledge of the properties

of radio waves gives us an idea of waves of light or even X rays.)

When this research had been completed, the atomic hypothesis was accepted even by its most famous enemy, the German chemist Friedrich Wilhelm Ostwald (1853-1932). In 1909, Rutherford, who had shown that atoms are of complex structure, discovered, in collaboration with the research student Thomas Royds, the most convincing proof of the atomic structure of matter. This came about as follows.

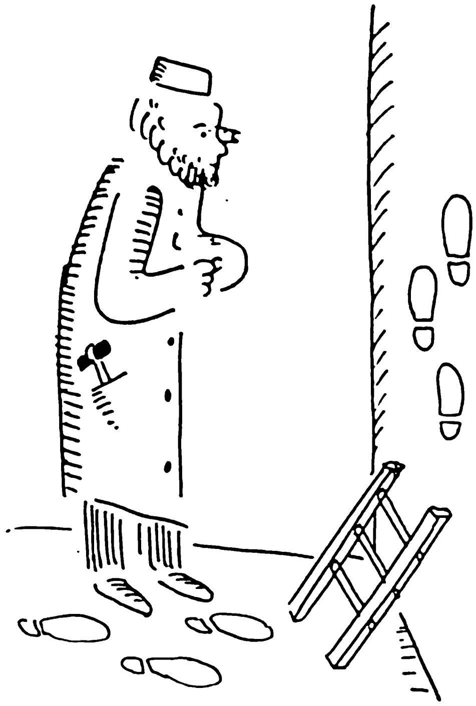
It had long been observed that helium accumulates in minerals containing the radioactive substances thorium, uranium and radium. It had even been measured that one gram of radium, in a state of radioactive equilibrium, evolves 0.46 mm^3 of helium daily, i.e. 5.32×10^{-9} cm^3 per second. After the nature of alpha particles had been established, there was no longer anything miraculous about this fact. But Rutherford went further: he *counted* the number of alpha particles emitted per second by one gram of radium. It is a large but quite definite quantity: 13.6×10^{10} particles per gram-second. These alpha particles capture two electrons each and become atoms of helium in which form they occupy a volume of 5.32×10^{-9} cm^3. Consequently, one cubic centimetre contains

$$L = \frac{13.6 \times 10^{10}}{5.3 \times 10^{-9}} = 2.56 \times 10^{19} \text{ atoms}$$

But this is the well-known Loschmidt's number that he derived on the basis of the molecular-kinetic hypothesis! As a matter of fact, one gram-atom of helium (and any other monoatomic gas) occupies a volume of 22.4 litres and contains 6.02×10^{23} atoms, i.e. in one cm^3 there are

$$L = \frac{6.02 \times 10^{23}}{22.4 \times 10^{3}} = 2.69 \times 10^{19} \text{ atoms}$$

This coincidence is convincing.



But people have an inexplicable requirement: before a person will finally admit that something exists, he has to see it with his own eyes ("You gotta show me," said the proverbial Missourian). Strictly speaking, this is unfounded: we repeatedly become victims of optical illusions. This peculiar need of human cognition was duly satisfied in 1911 by Charles Thomas Rees Wilson (1869-1959), the Scottish physicist. After fifteen years of research he developed his famous cloud chamber which enabled the motion of separate alpha particles to be followed by observing the tracks made by them.

Obviously, the significance of this invention was not in the fact that it appeased the whims of human psychology. In the hands of physicists it became a new and effective instrument for research on the structure of the atom.

By 1912 there were as many as thirteen methods of determining Avogadro's number. The explanation of a great many different phenomena, unrelated on the face of it, depend upon its numerical value. Among

them are the Brownian motion and the blue colour of the sky, the viscosity of gases and the black body spectrum, radioactivity and the laws of electrolysis. This number N turned to be very large, but not infinite. Like the number of people living on the earth, it cannot be fractional. And what is more, we now know Avogadro's number

$$N = 6.022169 \times 10^{23}$$

to a considerably greater degree of accuracy than the earth's population.

"If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* (or the atomic *fact*, or whatever you wish to call it) that *all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another*. In that one sentence, you will see, there is an *enormous* amount of information about the world, if just a little imagination and thinking are applied."

These words were written by our contemporary, Richard Phillips Feynman (born 1918), who won the Nobel Prize in physics in 1965. Though, in a sense, they repeat Democritus, almost word for word, the conceptual ideas and images that we link with these words today are entirely different; many new facts about the atom have been ascertained in 25 centuries.

This was not a simple task—only the results of scientific research are simple, and they do not depend upon the personality of the investigator. This makes them the more valuable.

ROUND AND ABOUT THE QUANTUM

INDIVISIBLE ATOMS

The breath-taking advances of scientific knowledge have relegated venerable arguments in favour of the existence of atoms to the realm of history. Some of them, however, may prove of interest to us.

First of all, those who believed in atoms asked their opponents the simple question: "How can the same amount of matter, if it is not made up of atoms, occupy different volumes as we observe, for instance, in the compression and expansion of gases?" Then they produced proofs of the smallness of atoms and their enormous quantity. For example, one needle-shaped crystal of indigo can dye a whole ton of water. A case was recollected in which one grain (0.062 grams) of musk had filled a large room with its odour for twenty years without undergoing any visible changes.

The development of the exact sciences undermined the faith in reasoning even of the most likely kind. It was replaced by quantitative evaluation.

Even Newton evaluated the thickness of soap films and proved that it is one-fiftieth of the wavelength of light and equals 10^{-6} cm $=100$ Å. Following his example, many physicists (including Lord Kelvin) conducted investigations into the properties of soap bubbles.

Since the time that Benjamin Franklin poured a teaspoonful of oil on the surface of the pond in Clapham Common near London, his experiment was often repeated in different versions. Lord Rayleigh, for instance, prepared oil films as thin as 16 Å and, in 1890, Röntgen succeeded in reducing the thickness of such films to 5 Å which is only five times the diameter of an atom of hydrogen.

Faraday made gold foil only 10^{-6} cm thick, and by precipitation on glass from a solution he obtained gold

film only 10^{-7} cm thick, that is only one-tenth of the thickness of a soap bubble. Such gold films are transparent and their thickness is only ten times the diameter of the atoms.

Among other attempts to determine the size of atoms mention should be made of the unjustly forgotten work of Thomas Young (1773-1829). In 1805, in studying the phenomena of the capillarity and surface tension of liquids, he came to the conclusion that the size of atoms does not exceed 10^{-8} cm.

ATOMS AND THE VOID

Even people that easily bend horseshoes admit that atoms are solid and hard; in childhood they too banged their knees against the corners of furniture. Hence, it is immensely difficult to imagine that an atom is as empty as the space between the earth and the sun, and, at the same time, exceptionally stable.

We know, for instance, that water remains water even when subjected to a pressure of 10 thousand atmospheres. This is a very high pressure, approximately that obtained if the weight of a good-sized elephant was supported by an area of one square centimetre. Simple calculations show that each atom is subject to a force of about 10^{-9} grams, that is, a hundred million million (10^{14}) times its own weight (10^{-23} grams). This is the same as if we loaded a hundred Chomolungmas (Mount Everests) on the back of our elephant.

All this may be astonishing, but it doesn't prevent atoms from being empty, staggeringly empty: the nuclei of all the atoms of which Chomolungma is made can be stuffed into the sleeping bag of either the Sherpa Tenzing Norgay or Sir Edmund P. Hillary who first climbed this peak.

We don't know what a turn the history of the atom would have taken if physicists hadn't invented the diffraction grating.

It was first used by Fraunhofer in 1819, Ångstrom made it the principal instrument in his investigations and, finally, Rowland developed it almost to its present form. The principle of the grating is based on the phenomenon of diffraction, i.e. on the capacity of waves to bend around an opaque barrier if its size is comparable to the wavelength. Waves of different length bend differently around the barrier, thereby enabling them to be separated and measured.

Owing to the application of this instrument, the accuracy of measurement achieved in spectroscopy is surprising, even for physics. As far back as the turn of the century, it was possible to separate two lines in the visible range of a spectrum if their wavelengths differed by at least 10^{-3} Å (today the accuracy has been increased to 10^{-4} Å).

To get an idea of the precision of such measurements, just imagine that you undertake to measure the length of the equator to an accuracy within one metre. There is, of course, no need for such a measurement, nor any point in making it, simply because the result will be influenced by each ant hill along the way. But in spectroscopy, such efforts are not made just for the fun of it, as the further history of the atom has convincingly proved, in spite of the distrust and scoffing that sometimes accompanied such efforts. This is borne out by the history of the standard metre.

The famous platinum-iridium bar with two transverse parallel scratches, cast by a decision of the French National Convention and kept under a bell glass at the International Bureau of Weights and Measures at

Sèvres, near Paris, was found not to be exactly equal to one ten-millionth of the distance from the equator to the north pole, measured along the meridian of Paris, as it was supposed to be.

The French academician, Jacques Babinet (1794-1872), was one of the first to express his doubt as to the expedience of such a length standard and proposed that the wavelength of some spectral line be taken for this purpose. Such a wavelength, he said, is a "quantity absolutely constant and independent even of cosmic cataclysms". His idea was first realized in 1892 by Michelson but was accepted only in 1958 when the new standard metre was legalized. The metre is now defined as a measure of length equal to 1,650,763.73 wavelengths in vacuum of the orange-red line of the spectrum of krypton-86.

JUST WHAT HATH RUTHERFORD WROUGHT?

The idea of the planetary structure of the atom was not such a rarity at the turn of the century as many science historians think today. Such ideas were openly presented even on the pages of certain textbooks.

As an example we can quote the following passages from the third volume of the *Cours d'electricité* published in 1907 and written by a professor of the University of Paris, Joseph-Solange-Henri Pellat (1850-1909).

"... the atom is not an indivisible particle of matter. The emission of light, producing spectral lines that are characteristic for each kind of atom, is in itself an indication of the diversity of atoms. It may be assumed that atoms consist of a large number of corpuscles which are attracted to some kind of centre, as the planets are attracted to the sun.

"For the neutrality of the atom it is necessary that the positive electric charge which, as we assumed, is

at the centre of the atom is equal in magnitude to the sum of the negative charge-corpuscles revolving about this centre.

"In a word, all the light, electrical, heat and mechanical phenomena can be explained if we assume the existence of two different kinds of matter: a corpuscle, or the negative electron, and the positive electron about which we know almost nothing. The central positive charge of the atom consists of a combination of positive electrons whose number varies according to the kind of atom being considered but is quite definite for each kind of atom.

"It is evidently unnecessary to demonstrate the elegance of this theory which enables all phenomena known up to the present time to be readily explained, and relates so many phenomena and laws together even though they do not seem to have anything in common."

A year later, the famous French physicist and mathematician Jules Henri Poincaré (1854-1912) wrote quite as definitely that "all the experiments on the conductivity of gases ... provide us with grounds for regarding the atom as consisting of a positively charged centre, of a mass approximately equal to that of the atom itself, about which electrons, attracted to this centre, revolve."

After reading these extracts, some admirers of Rutherford may be disappointed by his role in the history of the atom: he doesn't seem to have thought up anything new. This common error is due to the lack of understanding of the difference between science and natural philosophy. There is a strict rule in science: a discovery is made by the one who proves it. And you can prove something in science only by means of experiments and figures.

All the previous statements were based on pure speculation and therefore amounted to approximately

the following: the atom probably has such and such a structure. Only Rutherford was morally entitled to say: "This must be so. I can prove it with the pertinent figures. Anybody who wishes can check them if he repeats my experiments."

Mendeleev liked to repeat the proverb: "Sure, you can say anything, but you just go and try to prove it." This difference between a vague idea and a scientific proof should always be kept in mind in the arguments on priority of discoveries that blaze up from time to time in the history of science. It is reasonable in such cases to consider the founders of a theory to be those whose work, in virtue of deep-seated reasons or chance circumstances, has had a decisive influence on the subsequent development of science rather than those who first mentioned it. This may embody an element of purely human unfairness. But history is not based on moral considerations alone. Its task is the establishing of the true sequence of cause and effect and not the mollifying of resentment.

LIGHT PRESSURE

The hypothesis of light pressure first appeared in the times of Johannes Kepler who proposed it in 1619 to explain the origin and shape of the tails of comets. Nothing was known about the magnitude of light pressure and, as is common in such cases, incredible stories were told. In 1696, for instance, Niklaas Hartsoeker (who at one time was the teacher of the Russian czar Peter the Great) related the accounts of travellers who contended that the "current of the Danube River is much slower in the morning when the sun's rays oppose its flow, and is accelerated after midday when the sun's rays expedite its flow".

Until the end of last century, numerous attempts

to detect the pressure of light experimentally ended as complete failures. The cause of these failures became entirely clear as a result of the theoretical work of Maxwell and the successful experiments of Lebedev. The light pressure turned out to be very low. For example, even on a clear, sunny day, the pressure of the sun's rays on an area of one square centimetre does not exceed 0.82×10^{-10} grams. One poppy seed weighs a million times as much.

Chapter Four

PRE-BOHR TIMES * BOHR'S ATOM * POST-BOHR TIMES * FORMAL MODEL OF THE ATOM * NIELS HENRIK DAVID BOHR

Many of us, when we were young, day-dreamed of pirates and treasure ships. In our fervent fancy we re-lived the battle and the chase, mysteries of treasure islands and noble deeds. Almost real to us were these visions of frigates with crowded canvas, masts listed, scudding mutely through the blue seas and out of sight beyond the distant horizon, leaving only a foamy wake. At times, to increase the speed of their sailing ships, buccaneers took a desperate measure: they heaved their ballast overboard to lighten ship and escape pursuit. Often they got away with such risky procedures, but, from time to time, they were severely punished. The tall frigates, deprived of their ballast, became unstable and unmanageable as an eggshell under sail, and were capsized by the first blast of a coming gale.

This is, perhaps, the most difficult chapter in the book. At first glance, it may appear so humdrum and unwarrantably complicated that some readers will consider it to be unnecessary ballast. But this happens to be the same ballast that is loaded into the hold of

the frigate, and without which all the sails of our fancy are not only useless, but even dangerous. Too often, in a pursuit of speed and lightness, we neglect soundness and depth. Such unconcern, however, never remains unpunished. At some unexpected moment, our overfilled chalice of knowledge, unsupported by precise facts, capsizes, and we are obliged to begin anew.

There is nothing in this chapter that is incomprehensible to a thoughtful and unhurried reader. It will, however, require certain skills in systematic logical thinking. As a rule, these minimum efforts are subsequently rewarded by the greater fullness and "voluminosity" of the acquired knowledge.

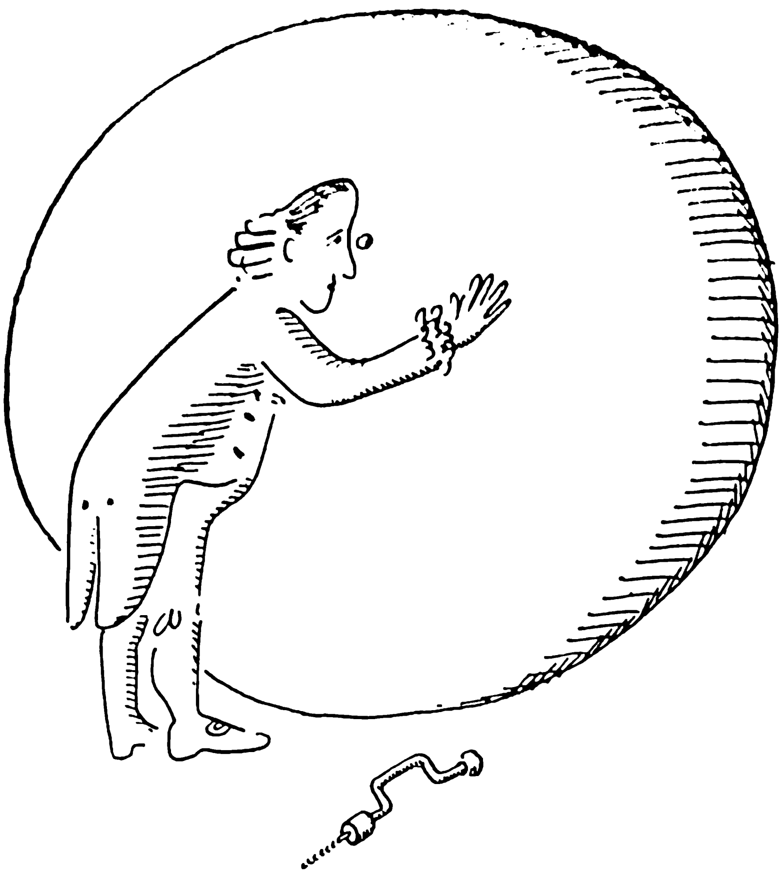
It may well be that after a first reading the chapter may raise more questions than it answers. No harm done. In return it will enable us to peek into the physicist's "kitchen" which is usually concealed behind the fashionable dinners and toasts proposed in honour of quantum mechanics. Of most importance is the fact that only such excursions into the depth of new ideas bring us the psychological sensation of their ordered structure and stability.

PRE-BOHR TIMES

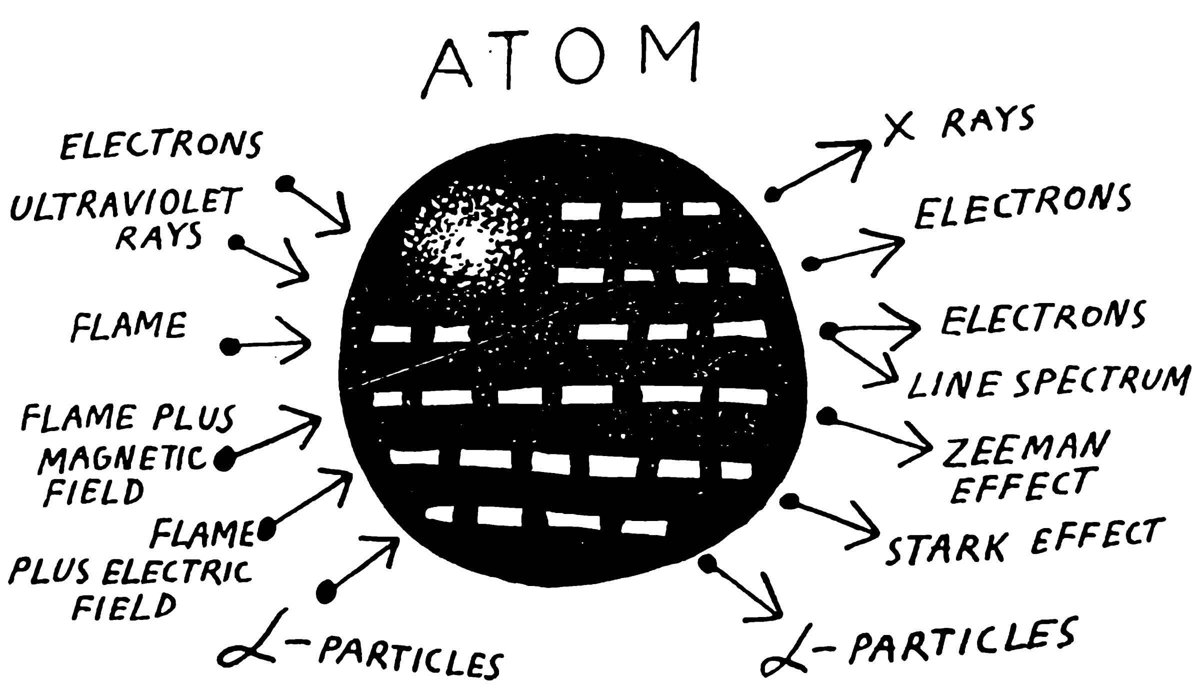
By the time that Niels Bohr (1885-1962) first appeared in Rutherford's laboratory in Manchester, a good deal was already known about the atom. So much that at times this hampered physicists in sifting out the main facts from the heap of available ones.

The diagram on the following page shows only those phenomena which turned out subsequently to be fundamental in understanding the structure of the atom.

On the basis of these facts (quite easy to observe) it was necessary to deduce the interior arrangement



of the atom, an item that nobody has ever seen nor will see. Problems of this type are generally known as "black box" problems. We know the nature of the action on the "black box" (our atom) and the results of this action. Thus we know *what* happens and *why* it happens. But this is not enough, we wish to know



more: *how* it happens, i.e. the mechanism of the phenomena taking place inside the "black box". This is much more difficult to accomplish than to reconstruct the action on the stage of a theatre from haphazard fragments of music and speech.

Even when we know all the external manifestations of the internal properties of the atom, it is still necessary to generalize and to synthesize them. This requires intuition which leads us infallibly through the gaps in the logical constructions to the only true picture of the phenomena.

Our far from complete diagram demonstrates the complexity of the problem before us. It is necessary to explain all these extremely diverse experiments from a single viewpoint (and not contradictorily). Niels Bohr found such an explanation. It turned out to be amazingly simple and of highly perfect form.

This happened when it suddenly became clear to Bohr that three physical ideas, *atoms*, *rays* and *electrons*, are related by the concept of a *quantum*. Up to this time, these ideas had developed independently. Chemistry and the kinetic theory of matter proved the existence of atoms. Maxwell's electromagnetic theory of light studied the properties of rays. The electrodynamics of Maxwell and Lorentz attempted to comprehend the concept of the "electron".

Even after the work done by Einstein and Millikan, nobody in Europe took the quantum of action h seriously, though there were various attempts to make use of it. In 1910, Arthur Haas tried to apply Planck's relation $E=h\nu$ to determine the boundaries and periods of motion of the electrons in Thomson's atom. John William Nicholson tried to use the idea of quanta in 1912 to analyse the spectra of the sun and various nebulas. In the same year, Walther Hermann Nernst proposed the hypothesis of quantized rotation.

The skeptical attitude to the idea of quanta was best expressed by Planck himself in a paper which he read before the German Chemical Society on December 16, 1911, almost eleven years after he had made his famous report. He said: "The simplest, so to speak, most naive explanation would be to attribute an atomistic structure to energy itself.... This was previously my own assumption, but I have given it up because I find it to be too radical...." In a book which he wrote a year later, Planck repeated the same ideas: "When you consider the complete experimental confirmation of Maxwell's electrodynamics in the most subtle phenomenon of interference, when you consider that a rejection of interference would lead to inconceivable difficulties for the whole theory of electrical and magnetic phenomena, you feel aversion to the destruction of these fundamentals in a single blow. For this reason, in the following we shall not deal with the hypothesis of light quanta, the more so since its development is still in the rudimentary stage."

Even as late as 1913 Arthur Schuster stated that he was sure that this theory was fatal to the wholesome development of science.

BOHR'S ATOM

By 1912 Niels Bohr had already begun work in Rutherford's laboratory in Manchester. Manchester is separated from continental Europe by half of England and the English Channel. Perhaps that is why the attitude toward the quantum hypothesis in Rutherford's laboratory was cautious, but without the apparent continental distrust. It may be that when Planck was still writing his book, Niels Bohr was already firmly convinced that "... the electron structure of Rutherford's atom is controlled by means of the quantum

of action". But a whole year of persistent speculation passed before he formulated his famous "Bohr's postulates".

What could his line of reasoning have been?

When Alexander the Great failed to untie the Gordian knot, he simply cut it with his sword. He was a resolute general and a conqueror. Bohr had a more difficult task but he acted in a similar way. He reasoned approximately as follows: according to the laws of mechanics the electron in Rutherford's planetary atom must revolve around the nucleus to keep from falling into it. But, according to the laws of electrodynamics, such rotation involves the radiation of energy by the electron which, ultimately, should fall into the nucleus anyhow. *We must prohibit it from falling into the nucleus.*

"Just a minute", arose objections, "what do you mean 'prohibit'? Do you admit that *electric forces* act between the electron and the nucleus?"

"Yes," answered Bohr.

"And that they are described by Maxwell's equations?"

"Yes."

"And that even the mass *m* and charge *e* of the electron are determined from *electrical* measurements?"

"Yes."

"Then the motion of the electron in the atom must also obey Maxwell's electrodynamics?"

"No!" said Bohr, ending the argument.

You must agree that such a method of conducting an argument can anger even a very calm person. "But, you see, the atom is nevertheless stable!" Bohr repeated endlessly in answer to all objections. "And we know no simpler reason for this stability than the fact that it exists."

In his search for a reasonable basis for this indubi-

table fact, Bohr ran across a book by Johannes Stark called *Principles of Atomic Dynamics* in which he first saw Balmer and Rydberg's formula. "Everything became clear to me at once," recalled Bohr. "After numerous attempts to apply quantum ideas in a more rigorous form, in the early spring of 1913, it occurred to me that the key to the solution of the problem of atomic stability was in the amazingly simple laws which govern the optical spectrum of elements."

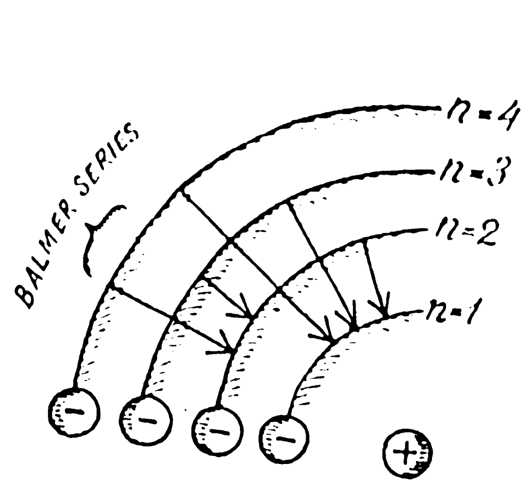
Now he could formulate his famous postulates:

First postulate—on the stationary states. *Electrons do not radiate electromagnetic waves when travelling on certain (stationary) orbits in the atom.*

Second postulate—on the quantum jumps. *Radiation of energy occurs only when an electron jumps from one stationary orbit to another.* In this case, the frequency of radiation is determined by Einstein's hypothesis on light quanta $\Delta E = h\nu$, where ΔE is the difference in energies of the levels between which the jump takes place.

In order to understand these postulates to a somewhat greater depth we can refer to the obvious analogy between the supposed revolution of an electron about a nucleus and that of a satellite about the earth. In his time, Newton discovered the law of gravitation when pondering over the question: "Why doesn't the moon fall on the earth?" Nowadays, this question can only be found in old jokes, because everybody knows the answer: "Because it is in motion, and at a definite velocity depending upon its distance from the earth." Thus, to keep a satellite from falling on the earth or flying away into space there must be a definite relationship between the radius r of its orbit and its velocity v along this orbit.

In the hydrogen atom a similar relationship exists between the velocity v of the electron, of mass m and



charge e, and the radius r of its orbit about the nucleus. This relationship can be written as the equation

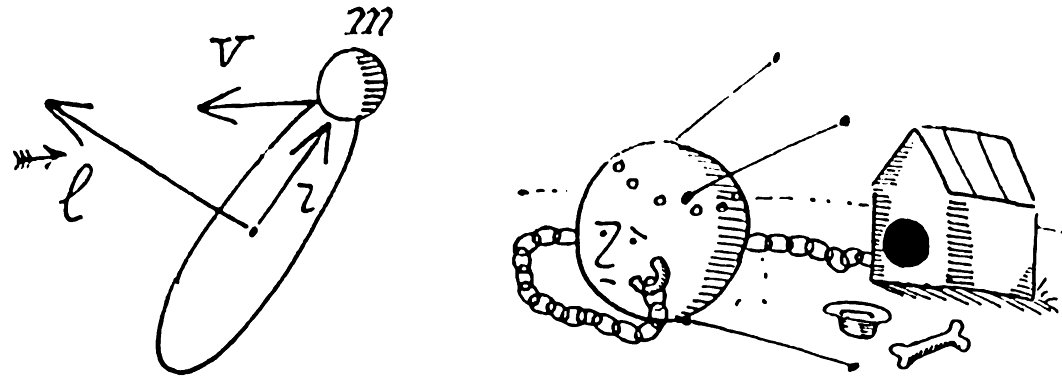
$$\frac{mv^2}{r} = \frac{e^2}{r^2}$$

This equation is always valid, irrespective of whether the electron radiates or not. It simply represents the well-known equality of the centrifugal and attractive forces.

If an electron loses energy on radiation (according to the laws of electrodynamics), it will fall into the nucleus, as does a satellite upon being decelerated by friction in the atmosphere. But if special—*stationary*—orbits exist, on which the electron does not obey the laws of electrodynamics and, therefore, does not radiate, there must also be additional conditions which distinguish these orbits from a set of all possible ones.

The simplest way of demonstrating how these conditions originate is by continuing our analogy with the satellite.

In addition to the radius r of the orbit and the velocity v along this orbit, circular motion has still another characteristic: the angular momentum, or *orbital moment*, l. It equals the product of the mass m by the velocity v and by the orbital radius r, i.e. $l =$



$=mvr$. For a satellite it can have arbitrary values depending upon the values of r and v.

Bohr contended that an electron in an atom differs from a satellite in that its orbital moment l cannot be arbitrary. It must be equal to a whole, or integral, multiple of the quantity $\hbar = \frac{h}{2\pi}$ (this notation was proposed by one of the founders of quantum mechanics, Paul Adrien Maurice Dirac, and is referred to as "h bar". Thus

$$mvr = n\hbar$$

This, then, is the additional condition of Bohr that distinguishes stationary orbits (the only permissible ones in the atom) from the infinite number of conceivable ones). Since the quantum of action h plays the main role in such a selection of orbits, the whole process was called *quantization.*

Using the two preceding conditions, Bohr readily obtained the values of the energies E_n and radii r_n of the stationary orbits:

$$r_n = \frac{\hbar^2}{me^2} n^2 \quad \text{and} \quad E_n = -\frac{me^4}{2\hbar^2} \frac{1}{n^2}$$

Stationary orbits (and, consequently, energy levels) are numbered by integers n or k, which may have an infinite series of values: 1, 2, 3, ... In a transition from level n to level k an electron emits the energy $\Delta E=$

$=E_k-E_n$, and the frequency of the radiation that this involves is determined from Einstein's formula

$$\nu=\frac{\Delta E}{h}=\frac{E_k-E_n}{2\pi\hbar}$$

If we observe the radiation that occurs in the transition of an electron from all possible levels k to some definite level n, we will see a *series* rather than simply a collection of spectral lines. For instance, if $n=2$ and $k=3, 4, 5, 6, \ldots$, we will see the Balmer series. This at once leads to Bohr's famous formula for the frequencies of radiation of the hydrogen atom:

$$\nu=\frac{me^4}{4\pi\hbar^3}\left(\frac{1}{n^2}-\frac{1}{k^2}\right)$$

What do we find here?

Firstly, it reminds us of Rydberg's formula for the hydrogen atom. Rydberg had derived this formula empirically long before Bohr, as we related in detail in the preceding chapter. If Bohr's formula was correct it could be used to calculate Rydberg's constant R. Thus

$$R=\frac{me^4}{4\pi c\hbar^3}$$

It was calculated and its value actually did coincide with the one that had long been known from spectroscopic measurements.

This was the first victory of Bohr's theory, and it had the effect of a miracle.

But this was only the beginning. It followed from Bohr's theory that the radius of a hydrogen atom in the ground (unexcited) state ($n=1$) equals

$$r_1=\frac{\hbar^2}{me^2}=0.53\times10^{-8}\text{cm}=0.53\ \text{Å}$$

This means that the size of atoms ($\approx10^{-8}$ cm) cal-

culated by Bohr's formula coincides with the predictions of the kinetic theory of matter.

Last, but not least, Bohr's theory explained how the properties of a line spectrum are related to the internal structure of an atom. This relation had always been sensed by intuition. But it was Bohr who first succeeded in expressing it *mathematically*. It was found that the required relationship is accomplished by Planck's constant h.

This was not to be expected. As a matter of fact, the quantum of action h originated in the theory of thermal radiation and was in no evident way related to atoms or to the rays these atoms emit. Nevertheless, this is precisely what enabled the size of the atom to be calculated and the frequency of the light it emits to be predicted. What helped Bohr, as many before him, to guess this relationship was his profound faith in the unity of nature.

Bohr's postulates (like any other postulates) cannot be substantiated logically nor derived from more simple ones. They remain arbitrary creations of human reason until experiment confirms the consequences following from them. Then theories are developed on their basis, and the most apt of these theories will be called laws of nature.

We shall confine ourselves to only these three consequences of Bohr's theory. Actually, there are considerably more of them and they all demonstrate the incomprehensible force of these incomprehensible postulates.

Bohr, of course, arrived at these postulates along a somewhat different way than we have just now. When someone climbs an unfamiliar peak for the first time, you can hardly expect him to take the shortest road. Only after reaching the summit can he see a much easier way.

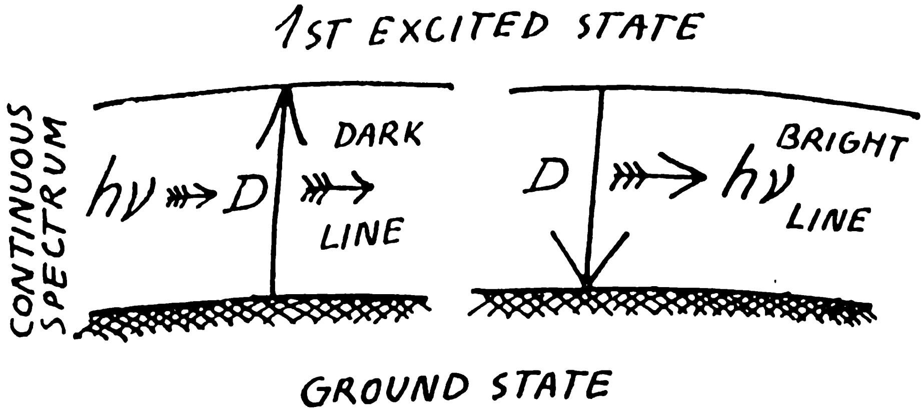
Notwithstanding the unusualness of Bohr's postulates, his theory was soon recognized and found quite a number of talented and keen followers. If we were to define the attitude of physicists in those days toward the new theory, it would be appropriate perhaps to mention a feeling of relief, a feeling of liberation from the continuous stress which they had been subject to in their attempts to retain a heap of disconnected facts in their memories and to make ends meet somehow. Now, naturally, all atomic phenomena were grouped about an incomprehensible but simple model which brilliantly explained some of them. Others required a further development of the model.

In particular, Kirchhoff and Bunsen's experiment with the sodium vapours could be very simply explained.

As a matter of fact, until the ray from the incandescent body passes through the sodium vapour, whose atoms are in the ground state, it (the ray) contains waves of all lengths. Passing through the vapour, the ray transforms an atom of sodium from the ground state to the first excited one. This requires the expenditure of an energy quantum $E=h\nu$ of a frequency which exactly coincides with that of the D line of sodium. Consequently, after passing through the vapour the light no longer contains rays of this frequency and on the spectrograph scale we see a continuous spectrum, intersected in the yellow region by the dark D line.

In the reverse process, when the sodium atoms return from the excited to the ground state, they emit light of the same frequency ν that they have previously absorbed. Again we see the same D line, but now it is bright yellow.

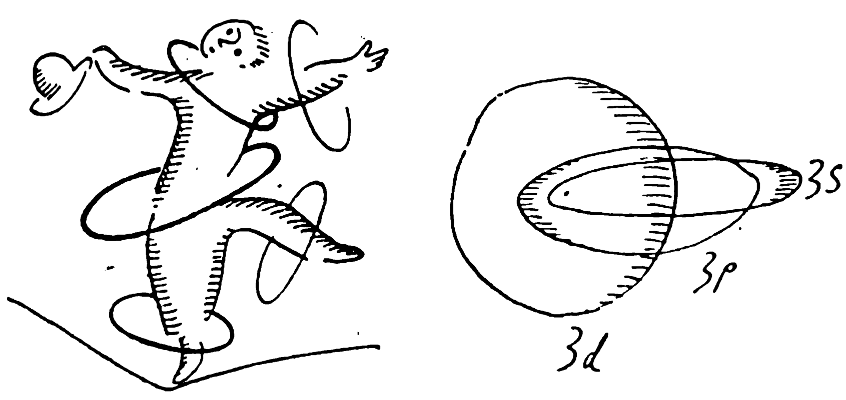
In spite of the fact that Bohr's theory enjoyed great



success, physicists first accepted it rather as a convenient model. They had no strong belief in the reality of such an energy ladder in the atom. This doubt was settled in 1913 by James Franck (1882-1964) and Gustav Ludwig Hertz (born 1887), a nephew of the famous Heinrich Rudolf Hertz. Like any clear idea, Bohr's theory not only explained old facts, but also suggested ways by means of which it could be checked.

Arnold Johannes Wilhelm Sommerfeld (1868-1951), an outstanding physicist and brilliant teacher, was one of the first in Europe who not only accepted Bohr's postulates at once, but developed them further, "... following, as once Kepler had in studying the planetary system, his inner feeling of harmony". He reasoned as follows: if an atom is similar to the solar system, then an electron in such a system can travel both along a circle, as in Bohr's model, and along ellipses as well, the nucleus being at one of the foci of the ellipses.

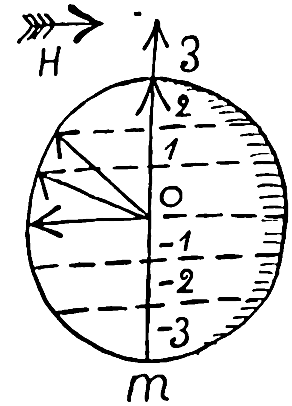
Ellipses with the same major semiaxis belong to the same value of the *principal quantum number* n

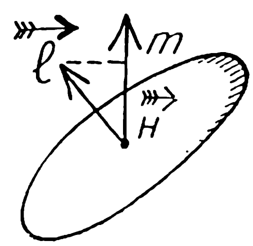


because electrons on such orbits have equal energy (Sommerfeld, of course, could prove this, but we shall just have to believe that it is so). The ellipses are distinguished from one another, however, by the degree of ellipticity which depends upon the orbital angular momentum. Entirely on the same lines as Bohr's ideas, Sommerfeld supposed that for a given n value the ellipses can be flattened to different degrees of ellipticity, not arbitrarily, but only so that the *orbital quantum number* l (which distinguishes them) can have only integral values: $l=0, 1, 2, \ldots, n-1$. Thus the number of permissible ellipses cannot exceed the principal quantum number n, which is the number of the stationary state.

But this was not all that Bohr and Sommerfeld could explain. If Einstein's theory of relativity is taken into account, it is found that the energy of the electron differs slightly on the various ellipses. Hence, the energy levels in the atom must be specified by *two* quantum numbers, n and l. For the same reason, the spectral lines produced in transitions of the electron between levels with different n values should have a *fine structure*, i.e. they should split into several components. At Sommerfeld's request, Friedrich Paschen checked and confirmed this inference of the theory by the example of the spectral line of helium with $\lambda=4686$ Å, which corresponds to a transition from level $n=4$ to level $n=3$ (from the fourth to the third level). After carefully examining a photograph of a helium spectrum, he found the line actually to consist of thirteen closely spaced lines.

This was an astonishing correspondence, and at that time (in 1916) it was compared with the calculations of Urbain Jean Joseph Leverrier and John Couch Adams who predicted the existence of the planet Neptune.





But even two quantum numbers did not explain all the features of spectra. For instance, if the radiating atom is placed in a magnetic field, the spectral lines are split in an entirely different manner.

As far back as 1862, in his last (and unpublished) work, Faraday made attempts to observe the splitting of spectral lines in a magnetic field. The magnet that he used in these experiments proved to be too weak and only in 1896 did Pieter Zeeman (1865-1943) observe the phenomenon that Faraday had searched for in vain.

Following the work of Bohr and Sommerfeld, the splitting of spectral lines in a magnetic field was explained as follows. Imagine that you have before you an electric motor. Without concerning ourselves with the technical details of its design, we know that the rotor will begin to rotate when an electric current is passed through the winding. An electron travelling along a closed orbit in the atom is similar to a turn with current in the motor winding. And exactly in

the same manner as this turn, the orbit of the electron in a magnetic field begins to rotate. In contrast to the turn, however, the orbit cannot occupy arbitrary positions in the atom because this is prevented by quantum laws. The essence of these quantum laws can be readily understood from the diagram. Here the magnetic field is directed upward and the orbit of the electron is shown edgewise, the radius of the orbit being numerically equal to the orbital angular momentum l (in the figure $l=3$). It was found that the laws of quantization permit only such positions of the plane of the orbit with respect to the magnetic field H in which the projection of the diameter of the orbit on the direction of the field H is an *integer*. This third number, the *magnetic quantum number* m, as can be readily seen, may take the values $m=l$, $l-1$, ..., 1, 0, -1, ..., $-(l-1)$, and $-l$, or $(2l+1)$ values in all.

Thus, in a magnetic field, each energy level E_{nl} with specified values of the quantum numbers n and l can be further split into $(2l+1)$ sublevels E_{nlm}, each of which is uniquely distinguished by specifying *three whole* quantum numbers: n, l and m. This leads to additional splitting of the spectral lines.

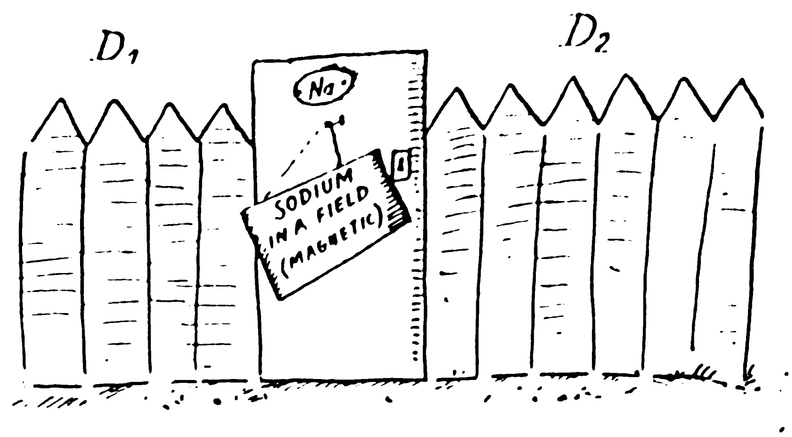
As it became more complicated, Bohr's theory gradually lost its initial elegance and visualizability. It was replaced by the *formal model of the atom* which was to meet a single requirement: to provide proper systematics of the spectral terms, or energy levels. The word "quantization" gradually lost its initial meaning; it now signifies the formal process of associating *whole* (quantum) numbers n, l and m with each energy level in the atom or, more precisely, with the kind of motion the electron is in. Quantum numbers n, l and m determine the stationary orbits in an isolated atom. External fields (both electric and magnetic) influence the motion of the electron in the atom

(splitting of energy levels). This immediately affects the structure of the light signal emitted by the atom (splitting of the spectral lines).

FORMAL MODEL OF THE ATOM

The writing of books on science, understandable to the general public, has its own limits (as does any science itself). As a rule, these limits are defined by the fact that at a certain moment it becomes impossible to employ the conceptions and images of everyday life any longer. To surmount this barrier it is necessary to go over to the language of formal concepts of science (at least primitive ones to begin with). Any attempts to avoid this step lead to the inevitable growth of unrealized, smouldering resentment, and the very essence of the science remains concealed. On the contrary, by overcoming certain minimum difficulties you can sense the power of the logical constructions of the science and appreciate the elegance of the consequences. As a rule, the technical difficulties that appear are not a bit greater than those encountered by any schoolboy studying chemistry. In almost no time at all he finds it much easier (and, above all, more understandable) to write the formula H_2O than to say each time: "a molecule consisting of two atoms of hydrogen and one atom of oxygen".

Something resembling chemical formulas has been adopted in the theory of spectra, where the principal quantum number n is denoted by the integers 1, 2, 3, ..., and the orbital angular momenta l by lower-case letters. The series of integers 0, 1, 2, 3, ... corresponds to the series of letter: s, p, d, f, ... Hence, the symbol $3s$, for instance, corresponds to an energy level with the quantum numbers $n=3$ and $l=0$, and the symbol $3p$ to the level with $n=3$ and $l=1$.

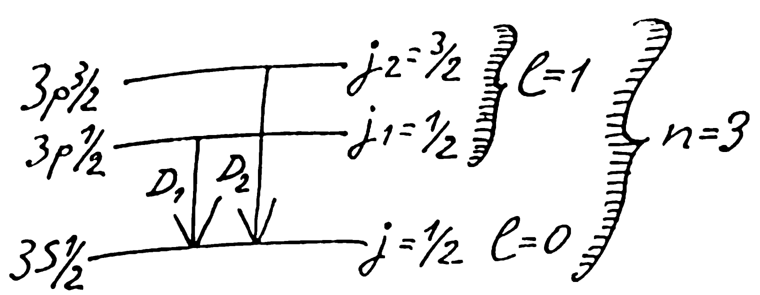


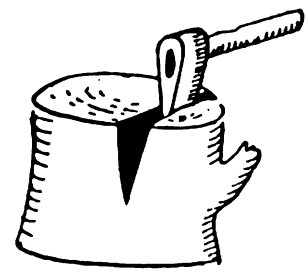
In an unexcited atom of sodium, the radiating electron is in the state $3s$. The dark D line appears when, upon exciting the atom, the electron goes over to the state $3p$. In the reverse transition $3p \rightarrow 3s$ the electron emits energy and the bright yellow D line appears.

What will happen when the radiating sodium is placed in a magnetic field? At first, after Sommerfeld, it was expected that the upper level $3p$ should split into 3 components, since $2l+1=2\times1+1=3$, and that the lower level would remain unchanged. As a result, each of the lines D_1 and D_2 should have split into three components.

Experiment contradicts such a conclusion. As is evident from the diagram, the D_1 line is split into four components and the D_2 line into six. This phenomenon is a special case of the so-called *anomalous Zeeman effect*. To understand its cause it will be necessary to revert to a question which we consciously avoided before: *why, even in the absence of a magnetic field, does the* D *line of sodium consist of two closely spaced components* D_1 *and* D_2?

Almost painfully pondering over this question, one of Sommerfeld's students, Wolfgang Pauli (1900-1958) approached the discovery of *electron spin* in 1924. His line of reasoning was approximately the following. Both lines, D_1 and D_2, correspond to the same transition from the level with $n=3$ and $l=1$ to

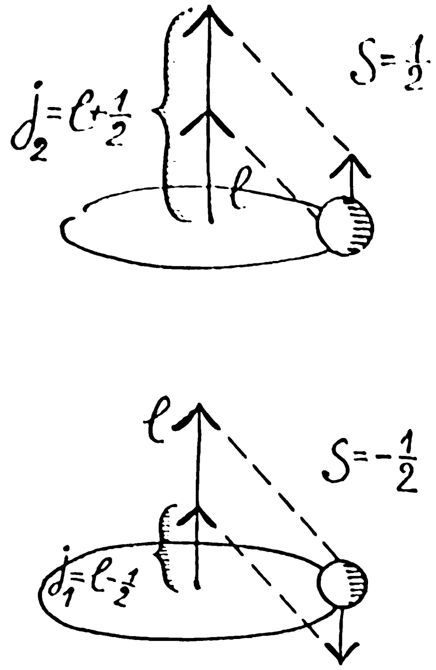


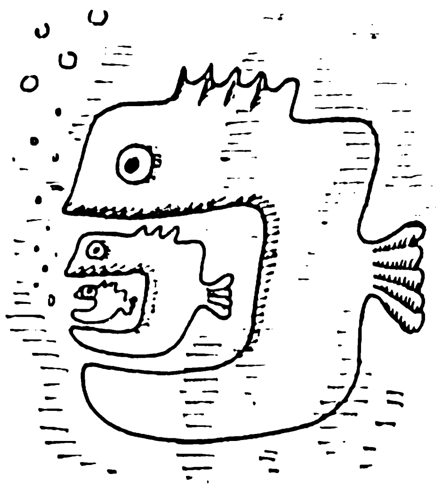


that with $n=3$ and $l=0$. But there are *two* lines! Consequently, not one, but two upper levels $3p$ exist and some kind of additional quantum number as well, that distinguishes one from the other. The property that corresponds to this *fourth quantum number* S he called "the nonclassical two-valuedness of the electron" and assumed that it could only have two values: $+1/2$ and $-1/2$. Pauli thought it impossible to visualize this property.

But within the next year, George Eugene Uhlenbeck (born 1900) and Samuel Abraham Goudsmit (born 1902) found a visualizable model to explain this property of the electron, assuming that it rotates about its own axis (spins). Such a model is a direct consequence of the analogy between the atom and the solar system. The earth not only travels along an ellipse about the sun, but also rotates about its own axis (this analogy was noted by Compton in 1921 and by Ralph Krönig in 1923, but Pauli was very much against such a visualization).

Uhlenbeck and Goudsmit suggested that, in addition to the orbital angular momentum l whose values are whole numbers and which occurs in motion along an ellipse, also inherent in the electron is the *inner angular momentum*, or spin S equal to $^1/_2$. Combined with the orbital angular momentum l, this inner angular momentum S can either increase or decrease it. As a result, the total angular momentum j is obtained.

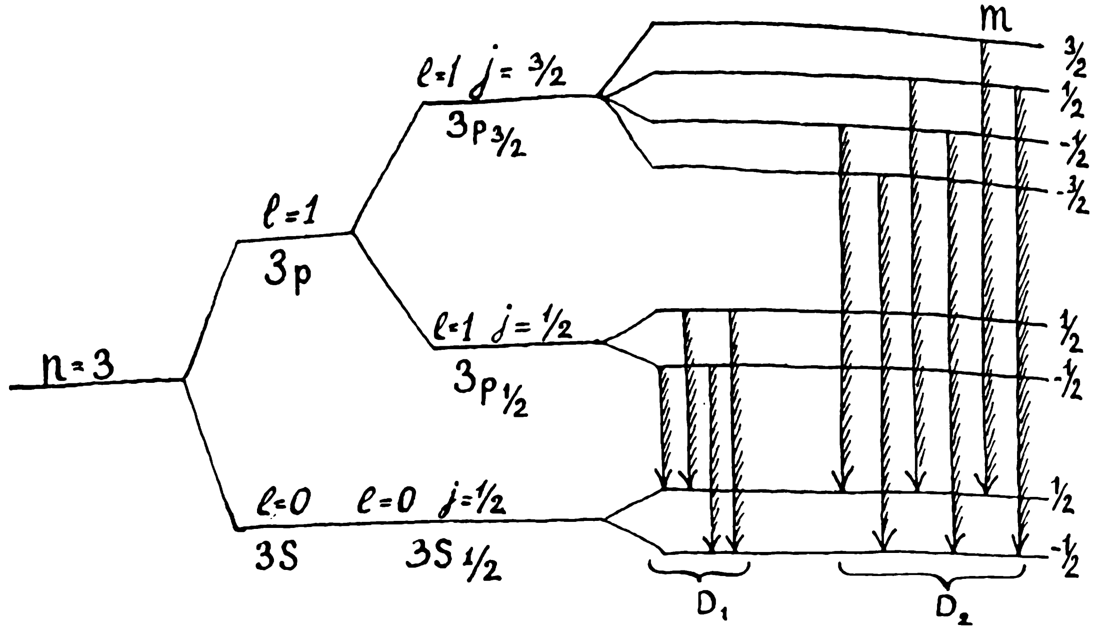




It equals either $j_1 = l - {}^1/_2$ or $j_2 = l + {}^1/_2$, depending upon the mutual orientation of vectors l and S. If $l = 0$, then the total angular momentum and the spin coincide ($j = S = {}^1/_2$).

Now, everything was cleared up. The $3s$ level in the sodium atom is not changed since it corresponds to the angular momentum $l = 0$, but the $3p$ level is split into two: $3p_{1/2}$ and $3p_{3/2}$ whose energies differ slightly. Accordingly, instead of one D line of sodium we observe two closely spaced spectral lines. The D_1 line corresponds to the electron transition $3p_{1/2} \rightarrow 3s_{1/2}$ and the D_2 line to the transition $3p_{3/2} \rightarrow 3s_{1/2}$.

In a magnetic field, each of the levels with a total angular momentum j (as in the case of the angular momentum l) is split further into $(2j+1)$ components which differ in the value of their magnetic quantum number m. Thus, each of the levels, $3s_{1/2}$ and $3p_{1/2}$, is further split into two sublevels, and the $3p_{3/2}$ level, into four. This results in the diagram of levels and transitions between them that is depicted on page 126 and which completely explains the structure of the spectral lines D_1 and D_2.



The diagram shows how Bohr's initial model with its single level having $n=3$ became more and more complicated. When the theory of relativity was taken into account, it split up into two lines: $3p$ ($n=3$ and $l=1$) and $3s$ ($n=3$ and $l=0$). With electron spin taken into consideration, the $3p$ level is further split into two sublevels: $3p_{1/2}$ ($n=3$, $l=1$ and $j=\frac{1}{2}$) and $3p_{3/2}$ ($n=3$, $l=1$ and $j=\frac{3}{2}$). Finally, in a magnetic field we obtain the system of levels, shown in our diagram, which produces the picture of spectral lines observed in an experiment.

The hypothesis of electron spin is one of the most profound ones in physics. No one has yet been able to fully comprehend its significance. Pauli was right, of course, when he cautioned against the oversimplicity of conceiving of the electron as a spinning top.

The influence of spin on the physical processes inside the atom is sometimes manifested in an entirely unexpected manner. One such feature of spin constitutes Pauli's famous exclusion principle which states that *it is impossible for any two electrons in the same atom to have four identical quantum numbers, n,*

l, m and S. Further on we shall see that only this principle enabled a rational explanation to be found for the periodic system of elements discovered by Dmitry Ivanovich Mendeleev.

From the foregoing, the reader has probably noted how much more meagre are the images used to describe the formal model of the atom when compared to Bohr's model, and how much more difficult it is to find everyday words that can help you to visualize this model. On the other hand, its power and scope have probably made themselves felt. By using the formal model we can explain and predict even the finest features of spectra. The appalling multitude of spectral lines could at last be brought into immaculate order. Now, to uniquely determine any line in the spectrum of an atom, it was sufficient to specify eight quantum numbers: four for the initial level of the radiating electron (n_i, l_i, m_i and S_i) and four for the final level (n_f, l_f, m_f and S_f).

By 1925 this titanic labour had been completed. The hieroglyphics had been deciphered, enabling the first, and still crude, picture to be drawn of the atom's internal structure.

Even today, of course, it is not a particularly easy task to decipher the spectrum of some element. It is a job that can be skillfully performed only by an expert. But, after all, it is not so easy to learn to read hieroglyphics either and, moreover, it is hardly necessary for everybody to acquire that skill. Since the key to the cipher has been found, anybody can learn to use it. Physicists are no longer oppressed by the long tables of spectral lines, just as the millions of species of plants and animals no longer terrify botanists and zoologists. After the works of Carolus Linnaeus, Chevalier de Lamarck and Charles Robert Darwin, they all conform to a strict classification.

The lot of spectral lines was much the same as that of the real Egyptian hieroglyphics. Until they were deciphered, they were of genuine interest only to Egyptologists. They were only of abstract interest to laymen. But when hieroglyphics and spectral lines had been deciphered, the former enabled the history of a whole people to be read, and the latter, to reveal the construction of the atom. These were matters of great interest to everyone.

Notwithstanding the success of the formal model of the atom, it did not satisfy the criterion of logical simplicity that produces an impression of obviousness (and which so favourably distinguished Bohr's model). Gradually, the formal model had become so complex that it aroused suspicion and a certain weariness, similar to that experienced by physicists before Bohr devised his model. Moreover, all attempts to extend Bohr's model to more complex atoms were failures. In a state of bewilderment, physicists began to doubt everything: the validity of Coulomb's law, the applicability of electrodynamics and mechanics to atomic systems and even the law of conservation of energy. Everyone understood, more or less, that this crisis had arisen from the clashing of empirical data, principles of quantum theory and the remains of classical conceptions which could not be rejected since nothing definite had, as yet, been proposed to replace them.

In the study of quantum phenomena, investigators continued to employ classical concepts. But the atomic objects had no properties that corresponded to these concepts, and therefore they were asking nature what were essentially illegitimate questions. Or, to be more precise, questions in a language that she did not understand. Then, a search began for a general principle on which the formal model of the atom and other features of atomic objects could be logically

based. "Let this unified principle be incomprehensible at first," was the general wish, "but let there be one and only one."

In the same year (1925), as if in answer to this wish, quantum mechanics, the science of the motion of electrons in the atom, was founded. It was created by a new generation of physicists. By a freak of chance they were all born almost at the same time: Werner Karl Heisenberg in 1901, Paul Adrien Maurice Dirac in 1902 and Wolfgang Pauli in 1900. Only slightly older were Louis de Broglie and Erwin Schrödinger. It was their good fortune to represent the images and concepts of atomic mechanics in the language of formulas. How they managed to do this, we shall find out a little further on.

NIELS HENRIK DAVID BOHR

The evolution of the "atomic" concept from Democritus to Bohr can be followed by means of a series of drawings. This is an instructive story, which always gives rise to a feeling of high esteem for the famed and unknown scientists concerned. Moreover, it evokes a feeling of amazement that such knowledge could be acquired at all, and in such a perfect and harmonic form.

As any truly great discovery, Bohr's discovery was hard to make but easy to understand. The might of Bohr's ideas is in their unprovable simplicity and intelligibility. Their main essence can be understood by any literate person. Bohr created the *image* which enabled us to find our bearings among the unusual *conceptions* of quantum mechanics. This image has become the symbol of our age. And when it is considered, moreover, that, in spite of its simplicity, this image correctly represents the principal properties of atoms, its outstanding features become evident at once.

The *Pioneer 10* Jupiter probe was launched on March

3, 1972. On board the spacecraft, which is to pass Jupiter on its way to the centre of the Milky Way galaxy, in addition to the instruments, there is an aluminium plate on which are etched two figures of a man and a woman, a diagram representing our sun and its planets and another diagram of the neutral hydrogen atom. People on the earth decided that this was the most important data to be included in a message to any extraterrestrial civilization that may be contacted.

Of a hundred physicists, taken at random today, hardly more than one or two have read Bohr's famous papers published in 1913. But any one of them can explain in detail the ideas set forth in these papers. This means that now Bohr's ideas have trespassed the boundaries of science and have become necessary elements of culture. This is the highest peak that any theory can reach. "A man who was destined to endow the world with a great constructive idea has no need for the praise of posterity. His creative work has endowed him with a more significant blessing." These words of Einstein on Planck can just as appropriately be said of Bohr.

Some years after the late war, in a trip to the Soviet Union, Niels Bohr visited the Georgian Republic. He spent one fine day with a group of Georgian physicists in the countryside at a village in the Alazani valley. Some of the local peasants were resting on the grass nearby, singing their native songs and drinking their native wine. According to age-old custom, the festivities were directed by a tamada, as toastmasters are called among the Georgian people. Niels Bohr was not only a great scientist, he was an inquisitive person as well. He approached the singers and was greeted with traditional cordiality.

The Georgian physicists began to explain, "This is the famous scientist, Niels Bohr...."

But the tamada interrupted them with an impatient gesture and, turning to his companions, proposed the following toast: "My friends! The world's greatest scientist, Professor Niels Bohr, is our esteemed guest. He founded modern atomic physics. His works are studied by schoolchildren all over the world. He has come to us from Denmark. Let us wish him and his companions a long life, much happiness and excellent health. Let us wish his native land peace and prosperity."

The tamada's speech was translated for Bohr word for word in a low voice. When the tamada finished speaking, an old man got up, carefully took Bohr's hand in his two hands and kissed it. After this, another mountaineer stood up, filled a drinking horn from a wineskin and, after solemnly bowing to Bohr, emptied it in a draught.

Niels Bohr had spent many years among the paradoxes of quantum mechanics, but even he was struck by the unreality of what was happening. Tears of astonishment and gratitude came to his eyes.

ROUND AND ABOUT THE QUANTUM

EXPERIMENTAL PROOF OF BOHR'S POSTULATES

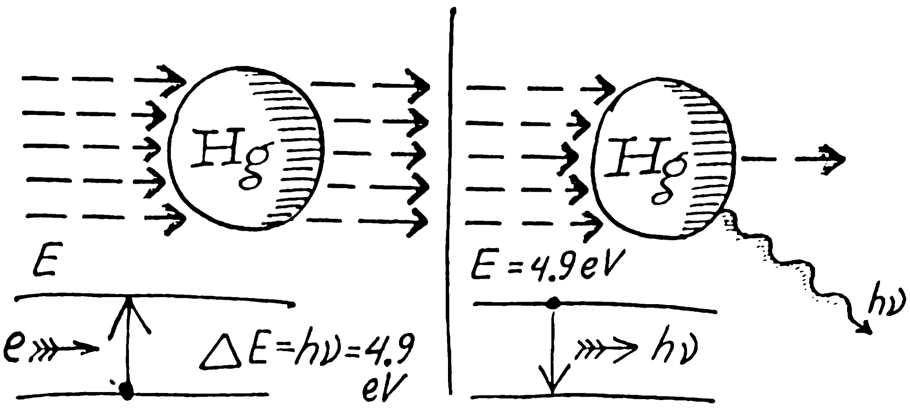
In essence, the experiment conducted by Franck and Hertz closely resembled that of Kirchhoff and Bunsen except that they replaced the atoms of sodium by mercury atoms and, instead of a ray of light, they directed a beam of electrons, whose energy they could vary, on the atoms. At this point, Franck and Hertz observed an interesting phenomenon: as long as the energy of the electrons was arbitrary, the number of electrons passing through the mercury atoms equalled the number of electrons in the initial beam. When,

however, their energy reached a certain definite value (4.9 electron volts, or 7.84×10^{-12} ergs), the number of electrons passing through the mercury was sharply reduced: they were absorbed by the mercury atoms. (It can be mentioned for comparison that the energy of the thermal motion of molecules at room temperature equals approximately 0.04 electron volts.) At the same time, a bright violet line with a wavelength $\lambda=$ $=2536$ Å appeared in the spectrum of the mercury vapour. This wavelength corresponds to a frequency of $\nu=1.18\times10^{15}$ s^{-1}. The energy of a quantum of such frequency is readily calculated; it equals $E=h\nu=$ $=6.62\times10^{-27}\times1.2\times10^{15}=7.82\times10^{-12}$ ergs, i.e. it is almost exactly equal to the expended energy of the electron. Evidently, this radiation is produced upon the return transition of a mercury atom from the excited to the ground state.

It is clear that the observed picture is a direct experimental proof of both of Bohr's postulates. Stationary states actually exist in the atom and it is therefore unable to absorb arbitrary portions of energy. Transitions of the electron between the levels in the atom are possible only in jumps, and the frequency of the emitted quanta is determined by the difference in the energy levels. It is calculated by Einstein's formula $\Delta E=h\nu$. This, of course, has become "clear" only now. In 1913, even Franck and Hertz interpreted their experiment in an entirely different manner.

"QUANTIZING" THE SOLAR SYSTEM

We have frequently compared the atom to the solar system, though we have not attached any profound meaning to this analogy. The more unexpected it will be to us then to find that the solar system, like the atom, also obeys a certain "quantization rule". This



rule has nothing in common with quantum mechanics, but, nonetheless, it is interesting to find that the distances of the planets from the sun (like the radii of the orbits in an atom) do not vary at random, but obey a fairly strict law.

This fact was known to Johannes Kepler, who, when still a young man, gave much thought to the "harmony of the spheres". He came to the conclusion that in the intervals between spheres constructed on the orbits of the planets it is possible to inscribe five regular polyhedrons.

In 1772, Professor Titius of Wittenburg published a book in Bonn called *Contemplation of Nature*. It contained a table of the distances from the sun to the planets in conventional units (the distance from the sun to the nearest planet Mercury being taken as 4). Thus

Mercury	$4 = 4$
Venus	$7 = 4 + 1 \times 3$
Earth	$10 = 4 + 2 \times 3$
Mars	$16 = 4 + 4 \times 3$
Jupiter	$52 = 4 + 16 \times 3$
Saturn	$100 = 4 + 32 \times 3$

with the addition later of

Uranus . . . . $196 = 4 + 64 \times 3$

Subsequently, Johann Elert Bode refined Titius' law, taking the distance to Mercury as 8 conventional units and writing the general formula for planetary distances in the form

$$R = 8 + 3 \times 2^n$$

where $n = -\infty$, 1, 2, 3, 5, 6, 7.

It is remarkable that in this scheme there is no planet with the number $n=4$, which would have been located between Mars and Jupiter. But this is where the belt of asteroids, or minor planets, are. Astronomers are of the opinion that these are fragments of a large planet, Phaëthon, that once existed.

The Titius and Bode law has not yet been fully understood though several proofs exist. Evidently, a complete explanation of this law will be found when we finally discover the origin of our solar system.

Chapter Five

TEACHINGS OF THE ANCIENTS *
FIRST ATTEMPTS * ELEMENTS AND ATOMS *
TABLE OF ELEMENTS *
EXPLAINING THE TABLE

Imagine that you have decided to study the life of a cell. You perform all possible experiments on it: you heat it, expose it to radiation, demolish it and examine it carefully in a microscope. All your knowledge of the cell will be incomplete, however, unless you realize that a cell is a part of a living organism and only as such does it display its properties fully.

Something similar took place in the science of the atom. Up till now we have purposely tried to isolate the atom and have selected only those experiments that can throw some light on the properties of a separate atom. But long before all those experiments showed the complex structure of the atom, Dmitry Ivanovich Mendeleev (1834-1907) had established that the atoms of various elements made up a single organism: the *natural system of elements*.

A year after he devised his periodic system of elements he wrote: "It can readily be presupposed, though as yet it is impossible to prove, that atoms of elementary bodies are complex substances made up of certain

smaller parts (ultimates), and that what we call the indivisible (atom) is indivisible only by ordinary chemical means. In spite of the precariousness and arbitrariness of such a presupposition, the mind involuntarily yields to it upon acquiring a knowledge of chemistry. That is why such a doctrine has been repeated in various forms for so long a time, and my proposed periodic relationship between properties and weight evidently confirms such an intuitive presumption, so to speak, peculiar to chemists."

It must be said that chemists could never be satisfied with the idea of a large number of independent qualitatively different elements. Consequently, they always tended to reduce this qualitative diversity to a simple and clear idea: the atoms of the various elements are different aggregates of particles of the same kind.

Such attempts began in ancient times and developed subsequently along two different ways.

Democritus believed that all substances in nature were built up of atoms, and that the properties of substances depended upon the different combinations of their component atoms.

Aristotle contended that all existing things consisted of elements which themselves were carriers of definite qualities.

An echo of this ancient controversy has even reached our times: when we hear the word "atom", it involuntarily calls forth the visual image of something hard and massive; at the words "chemical element" we try to imagine some pure quality, regardless of its carrier. Perhaps this is why the study of chemical elements first began to develop entirely independently of the idea of atoms. Subsequently, both teachings became so interknitted that they could no longer be distinguished from each other. But, as we just had rea-

son to see, we have still not surmounted the psychological barrier between them.

The ways of science are unfathomable, and the sources are many. Up to this point we have followed the "physical sources" of the science of the atom in some detail. The time has come to reveal its "chemical sources".

TEACHINGS OF THE ANCIENTS

Philosophers of the Ionian school, whose famous representative was Thales of Miletus (c. 640-546 B.C.), recognized only one basic element—water—"on which the earth floats and which is the beginning of all things". Later, Empedocles of Agrigentum (c. 490-c. 430 B.C.) added three more elements—earth, fire and air—to water. Finally, Aristotle (384-322 B.C.) added a fifth essence (or, in the Latin, *quinta essentia*), of which the heavenly bodies were supposed to have been made, to the other four elements. Aristotle considered this essence to be the ultimate in perfection. This meaning has come down to us today in the word "quintessence".

Somewhat similar teachings are found in ancient Hindu philosophy. But, in contrast to the Greeks who were materialists and understood elements to be *matter* that influences our sensory organs, in India the elements were conceived of as manifestations of the Universal Soul or Essence of the Universe. There were five such element-manifestations in Hindu philosophy, one for each of the senses capable of perceiving them: ether for hearing, wind for the touch, fire for sight, water for the taste and earth for the smell. Kanada, a Hindu philosopher we mentioned at the beginning of our quest, added four more elements: time, space, the soul (Atman) and manas (means by

which the impressions of the senses are transmitted to the soul). Moreover, he contended that four of the elements: earth, water, fire and air, consisted of atoms.

In the Middle Ages, the doctrine of the elements was revived by the alchemists, the most famous of which were the Egyptian Zosimus (about 300 A.D.) who wrote a 28-volume encyclopedia on chemical knowledge up to his day, the Arab Geber (Abu-Mousa-Djaber ben Hayyan Ec Coufy, c. 760-815 A.D.) and Saint Albertus Magnus (Albert von Bollstadt, c. 1193-1280), also known as Albert the Great, the Bavarian scholastic philosopher.

The alchemists (after Aristotle) conceived of the elements as being *qualities* or "principles" and not substances. Mercury served as the "principle" of metallic lustre, sulphur—combustibility, and salt—solubility. They were sure that if these "principles" were mixed together in the proper proportions, any substance in nature could be obtained.

As a rule, the word "alchemy" is associated with tales of attempts to change mercury into gold, the concocting of the elixir of life and other miracles. A little rummaging in archives may turn up, for instance, a work of Geber in which he seriously discussed the question: "Why, as everyone knows, a cloud provides no rain when a naked woman comes out of her house and faces this cloud?"

But, in addition to this obvious nonsense, alchemists did invent alcohol which in itself is sufficient to justify their existence. Their main service to mankind, however, is that the blind experimenting the alchemists were wont to practice, although with no adequate direction or knowledge, gradually led to the accumulation of facts without which the science of chemistry would never have been founded.

FIRST ATTEMPTS

In the seventeenth century, alchemy and natural philosophy made way for chemistry and physics. In 1642, Joachim Jungius (1587-1657) published his *De Principis Naturalim*. He closes these *Disputes on the Principles of Matter* quite in the spirit of the century, with the words: "Which principles should be recognized as primary for homogeneous bodies is a question that can be answered only by honest, detailed and diligent observations rather than by making guesses."

A famous book, *The Sceptical Chymist*, written by Robert Boyle, was published in 1661. In it he defines chemical elements as simple or primitive substances that cannot be broken down into or be produced by uniting simpler substances.

In essence, this is the first and almost modern definition of an element: an element is primarily a *substance*, and by no means a "principle", substratum or idea. What still remained vague was how to extract elements from natural substances, and how to distinguish pure elements from their mixtures or compounds. For instance, Boyle himself supposed that water was almost the only pure element, and, at the same time, considered gold, copper, mercury and sulphur to be chemical compounds and mixtures.

Antoine Laurent Lavoisier (1743-1794) completely accepted Boyle's ideas on elements, but since he lived a century later, this was insufficient for him. He wanted to learn to separate elements out of chemical compounds. Evidently, he was one of the first to employ scales for purposes of investigation and not to prepare powders and mixtures. He proceeded from an assumption which seems trivial today, but which required no little courage in the age of phlogiston:

Each element of a compound weighs less than the compound as a whole.

Consecutively, applying this principle, he drew up the first table containing about 30 elements. The views of Lavoisier were so contradictory to the generally accepted ones that the zealous followers of the phlogiston theory in Germany burnt his portrait in public.

Lavoisier did not finish his investigations. Accused of treason, he was guillotined on the Place de la Rèvolution in the afternoon of May 8, 1794, and his body was buried in a common grave. Next morning, Joseph Louis Lagrange, the great mathematician, said bitterly: "It required only a moment to sever that head, and perhaps a century will not be sufficient to produce another like it."

The next hundred years were marked by the works of chemists who gradually added new elements to Lavoisier's table. Especially worthy of admiration is the "king of chemists", Baron Jöns Jakob Berzelius (1779-1848), who analysed over 2000 substances and discovered several new elements. (Incidentally, it was he who introduced in 1814 the modern notation of the chemical elements, using the first letters of their Latin or Greek names.)

By that time about 60 elements were known. This was not as many as Democritus had expected, but not so few that they could be regarded as being all independent. It certainly seemed probable that the set of elements formed a unified *system* and the search began to find one.

In essence, this search had begun a long time ago, when it was obviously premature, and had never ceased since. For example, as far back as 1786, Marne (Johann Bernhard Herrmann) was sure "that all that exists in nature is related together in a single conti-

nuous series" and that "... from the tiniest dust speck in a sunbeam to the holiest seraph among the angels, a whole stairway of creation can be erected...". In 1815, the English physician and chemist, William Prout (1785-1850), developed Marne's idea about the relationship of the elements and proposed the simple hypothesis that all elements were formed in the condensation of hydrogen.

This is neither the time nor the place for a detailed study of all the attempts to find a system of elements made at various times by Johann Wolfgang Döbereiner (in 1817), Max Joseph von Pettenkofer (in 1850), John Hall Gladstone (in 1853), William Odling (in 1857), Alexandre Emile Beguyer de Chancourtois (in 1863), John Alexander Reina Newlands (in 1865) and many, many others. It is considerably more important to retrace the train of ideas and motives that implemented this research.

At the basis of any science is the human capacity to wonder at things. The existence of elements always was and always will be a cause of wonderment. Isn't it strange that this whole world, filled to the brim with colours, odours, sounds and human passions, is built up of only several dozens of elements, whereas the elements themselves, as a rule, are plain in appearance and in no way resemble the colourful world built of them.

In the minds of scientists, however, the feeling of wonderment is soon followed by a pressing need to put the impressions they received into some kind of *order*. This purely human trait is deep within each one of us. A child rejoices when he manages to make a regular figure out of a chaos of building blocks, a sculptor when he carves a statue from a block of marble.

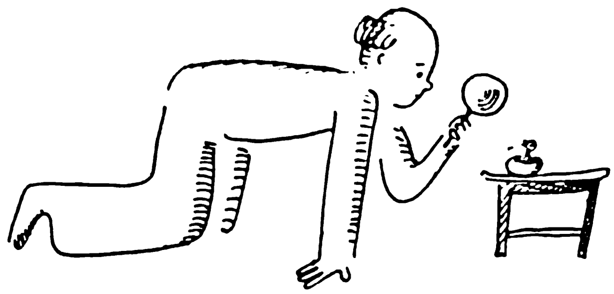
The first question that arises when we want to put things into some sort of order is: "On the basis of what

feature shall we do it?" If we have a box full of numbered wooden blocks in complete disorder, they can easily be put into order. It will be sufficient to put them into a line with increasing numbers. Now, just imagine that instead of blocks you have on hand test tubes with different chemical elements. The substances in the test tubes are of different colours and smells, they are liquid or solid, light or heavy. Which of these properties shall we take as the basis for our classification? For example, the test tubes can be arranged in a rack on a shelf so that their colours form a rainbow. This will be pretty, but quite useless for the science of the elements. Any classification makes sense only if it enables fundamental properties or structural features to be revealed. (Such, for instance, is the classification of the animal kingdom.)

What, in general, is the use of any classification, besides the fact that it satisfies our instinctive craving for simplicity? First and foremost, no science can exist without it. The brain of a scientist is only a small part of nature, and he can hope to know of all of nature only if he learns to pick out the main features from the great conglomeration of details.

This, precisely, is the essence of classification: to select only one or two properties from the great number possessed by various items or phenomena, but such that enable the laws of variation of all the other properties to be revealed.

Chemical elements have very many properties. This is quite understandable; otherwise they could not make up this diversified world of ours. The most important of their properties is the capacity to participate in chemical reactions. It would seem that exactly this property of elements should be taken as the basis of their classification. But this is not so: no method exists for accurately measuring (or even rigorously determi-



ning) the reactivity of elements. Without such measurements or determinations any classification is unreliable. To avoid being arbitrary a classification must be based on numbers, i.e. elements must be classified according to a property that lends itself to precise measurement.

But here also we encounter difficulties. We can measure the specific gravity of elements to great accuracy, but we cannot use it as the basis of their systematics, if only because they include gases, liquids and solids.

The many unsuccessful attempts to find a system of elements helped scientists to realize, finally, that among the various properties of elements that can be directly observed *not* a single one was suitable for the basis of their classification. The required property, *the atomic weight of the element*, lies outside of the dominion of chemistry; it belongs completely to physics. The moment when this was first realized can be regarded as the starting point of the modern theory of chemical elements. This decisive step was taken by John Dalton.

ELEMENTS AND ATOMS

Among the scientists of his time, John Dalton was a very unique figure. By the beginning of the nineteenth century everyone had come to believe in science and understood the secret of its power: it dealt with

numbers and numbers would never deceive you. Tha is why the art of conducting precise experiments wa valued higher than any other capability in those ti mes. Dalton absolutely lacked this skill and, conse quently, was subject to severe attacks from his more dignified colleagues and all the venerable scientists of his day.

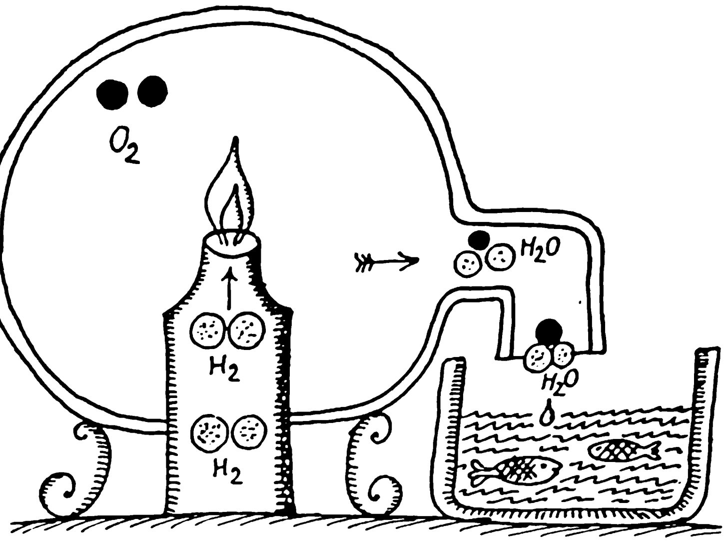
One of his biographers wrote that "his instruments of research, chiefly made by his own hands, were incapable of affording accurate results, and his manner of experimenting was loose, if not slovenly".

With respect to his cast of mind, Dalton was a typical theoretician, as we now picture this profession. Hence, the inaccuracy of measurement in his works should not be judged too strictly. On the basis of these works he expressed lucid and fruitful ideas that determined the further development of chemistry for the next hundred years. The gist of his discovery is that he *indicated an experimental way to verify the atomic hypothesis.*

Dalton defined the element as *a substance consisting of atoms of a single kind.* The atoms of different substances differ in weight and remain unchanged in all transformations of the substances; they are only rearranged. Dalton wrote that he would be as successful in trying to add a new planet to the solar system as in destroying or creating an atom of hydrogen.

The modern history of the atom begins with Dalton. He was the first who not only firmly believed in the atomic hypothesis, but began to search for its consequences, especially *observable* ones. His line of reasoning was approximately the following.

Assume that all elements consist of atoms. Then, say, 16 grams of oxygen contain N atoms of oxygen. Now assume, further, that we burn hydrogen in this oxygen. It can easily be measured that we need 2



grams of hydrogen to burn 16 grams of oxygen and that, as a result, we obtain 18 grams of water.

The first supposition that would occur to any supporter of the atomic hypothesis is that each atom of oxygen O combines with one atom of hydrogen H and forms one molecule of water HO. This is exactly what Dalton thought.

Subsequently, Berzelius proved that he was wrong about water, and that each atom of oxygen combines with *two* atoms of hydrogen so that the chemical formula for water acquires its familiar form: H_2O. But the important point here is the idea that a *whole* number of atoms of hydrogen combines with each atom of oxygen. Hence, if 16 grams of oxygen contain N atoms, then 2 grams of hydrogen contain $2N$ atoms. This means that *one atom of oxygen is 16 times heavier than an atom of hydrogen.*

Thus, it became possible to compare the weights of the atoms of different elements. This led to a new concept, the *atomic weight*, which is simply a number indicating by how many times the weight of an atom of some element is heavier than an atom of hydrogen. By definition, the atomic weight of hydrogen equals unity and, consequently, that of oxygen equals 16.

What use can be made of this simple argument? Firstly, we can measure the atomic weights of all other elements by observing how they combine with hydrogen and oxygen. We can determine, for example, that in the same 16 grams of oxygen only 16 grams of sulphur can be burned to obtain sulphur dioxide gas. What does this mean? We can, as always, make the simplest assumption: one atom of oxygen combines with each atom of sulphur according to the formula $S+O=SO$, from which we conclude that the atomic weight of sulphur is 16. But, as we know now, if combustion proceeds according to formula $S+O_2=SO_2$, then the atomic weight of sulphur must be 32.

This example shows that, by itself, the atomic hypothesis does not provide a method for predicting the composition of chemical compounds, but we can be wrong only a whole number of times. For example, we can predict that 32 grams of sulphur (containing N atoms) will combine with either N, or $2N$, etc. atoms of hydrogen, i.e. with 1 gram or 2 grams, but in no case with 1.35 grams of hydrogen. This statement is the content of the famous *law of multiple proportions*:

The ratio of the weights of elements combined in a compound is a whole multiple of the ratio of their atomic weights.

Dalton came to this conclusion in 1804-05, and in 1808 his famous book *A New System of Chemical Philosophy* was published. It ushered in a whole new age in science. His conclusions were immediately verified by the English physician and chemist William Hyde Wollaston (who had first discovered the dark lines in the solar spectrum), and he found them to be quite correct.

It is difficult for us today to picture that confused age when not only the atomic hypothesis was repudiated, but it was even doubted that chemical compounds

had a constant composition. One of the events of this period was the famed eight-year controversy between Joseph Louis Proust and Claude Louis Berthollet, which ended only after Proust had finally proved that irregardless of how a compound is obtained, it always has the same fixed composition. Water will always be water H_2O, whether it falls from the sky, is scooped out of the river or is obtained by the combustion of hydrogen in oxygen.

It remained to take the last step: to learn to determine the atomic weights of elements. For this purpose, it was necessary to start with the simplest substances. First scientists turned their attention to the gases. Very soon, in 1809, a former assistant of Berthollet, the French chemist Joseph Louis Gay-Lussac (1778-1850) (whom we know as the author of Gay-Lussac's gas law) made a very important discovery. He found that the volumes of two gases that combine in a chemical reaction are always in small whole number ratios.

Not the weights, as we see, but the *volumes*.

This is extremely important as we shall soon see. To obtain water, for instance, we must burn exactly two volumes of hydrogen in one volume of oxygen. This inevitably leads to the conclusion that equal volumes of gases contain equal numbers of atoms.

This was precisely the conclusion reached in 1811 by the Italian scientist Amedeo Avogadro, Count of Quaregna (1776-1856) (Lorenzo Romano Amedeo Carlo Avogadro di Quaregna e di Cerreto), except that his wording was more exact:

Equal volumes of gases contain equal numbers of molecules. As we now know, the molecules of most gases, such as hydrogen, oxygen, nitrogen, etc. consist of *two* atoms: H_2, O_2, N_2, etc. Now we can easily understand the classical experiment for the combustion

of hydrogen in oxygen. We know that from one volume of oxygen and two volumes of hydrogen we obtain two volumes of water vapour. This fact can be concisely written with the equation

$$2H_2 + O_2 = 2H_2O$$

What is the significance of Gay-Lussac's and Avogadro's discoveries and why have we spent so much time on these simple facts?

Let us retrace the line of reasoning again. Equal volumes of gases contain equal numbers of molecules. We know that 2 grams of hydrogen occupy a volume of 22.4 litres. We shall denote the number of molecules contained in this volume by N. The same N molecules of oxygen occupy the same volume of 22.4 litres, but weigh 32 instead of 2 grams. It follows that each atom of oxygen is 16 times heavier than an atom of hydrogen. This means that if we measure the *specific gravity* of any gas, we can immediately determine its *atomic weight*.

Nowhere, so far, has the reality of the atomic hypothesis been so evident. In fact, the specific gravity is a quantity that is readily measured and is customary since it affects our sense organs. It is astonishing that such a simple method can be used to measure the atomic weight, which is a quantity that we cannot sense directly, but which is, nevertheless, absolutely real.

The number N of molecules contained in 22.4 litres of any gas we now call Avogadro's number. This is one of the main universal physical constants, like the velocity of light c and Planck's constant h. To determine N it is sufficient to know the absolute weight M of one atom of hydrogen. Since 22.4 litres contain 2 grams of such atoms, the number $N = \frac{2}{M}$.

The number N could first be evaluated after the calculations made by Joseph Loschmidt who determined the absolute weight and size of an atom of hydrogen. Incidentally, it followed from his calculations that the distance between the molecules of a gas was approximately ten times the size of the molecules. If this had been known beforehand, then Avogadro's hypothesis would have been quite obvious: the mean distance between the atoms of a gas does not depend on their size, which varies only very slightly for different gases.

Avogadro's hypothesis was soon forgotten, and only half a century later, in 1858, it was revived by another Italian scientist, Stanislao Cannizzaro (1826-1910). This happened most opportunely because the chemists of that time could not come to any general agreement. Each one recognized only his own table of atomic weights, the organic chemists did not trust the inorganic chemists, and the First International Chemical Congress, a meeting of the world's most famous chemists held in Karlsruhe, Germany, in 1860, could not reach any satisfactory agreement on these matters. (Although, in a resolution dated September 4, 1860, the Congress did establish the difference between atoms and molecules.)

Many years later, the German chemist, Julius Lothar Meyer (1830-1895), who did much to establish the system of elements, recalled how, in returning from Karlsruhe on the train, he read Cannizzaro's pamphlet, and how "the scales fell from his eyes".

Now, finally, the matter of atomic weight was sufficiently clarified, and the atomic weights of the elements could be determined correctly enough to begin their classification.

What could be simpler, one would think? You only have to arrange the elements in the order of their increasing atomic weights, and the periodicity of their properties becomes evident by itself. The discovery of the periodic table is often narrated as follows. Mendeleev, after writing out the names of all the elements known at that time on the backs of his visiting cards, arranged them for a long time in various ways as if playing solitaire, until he dozed off. It was during this short nap that the solution came to him. Perhaps, this account is not fully authentic, but even those who regard it as the absolute truth should bear in mind that this fortunate day, March 1, 1869, was preceded by many other days and nights, sleepless and fruitless, when the problem seemed hopeless.

What, then, was the difficulty? Remember the example with the disordered pile of numbered wooden blocks. They can quite easily be put into numerical order. But there are no labels with numbers on the chemicals; they are merely substances of various colours; some are solid, others are liquid or gaseous. We know only that each one can be arranged according to a *number*—its atomic weight. This is the number that was first used as the basis of the classification. One can, of course, simply arrange all the elements in the order of their increasing atomic weights. This is exactly what many chemists did, but this is an occupation worthy of a mediocre apprentice, and not of a master. To begin with, how do we know that *all* the elements have already been discovered? Without being sure that they have, what sense is there in arranging them in the order of increasing atomic weights?

Actually, the problem resembles a toy picture puzzle

in which parts of a picture are depicted on the sides of wooden blocks, and the blocks must be arranged in such a way as to obtain the whole picture. Now imagine that some of the blocks have been lost and that the parts of the picture have been distorted on other blocks. It may still be possible to restore the whole picture but this, of course, will be much more difficult. This can be done, however, only if we try to conceive of the *picture as a whole*, and not just hope that it will come out by itself if we just rearrange the blocks thoughtlessly and at random.

This gift of synthesizing in his manner of thinking was one of Dmitry Ivanovich Mendeleev's strong points. From the very start, he did not conceive of the elements as a collection of random substances, but as parts of a single system. In his search for this system of elements, he did not confine himself to their physical properties alone,that is to their atomic weights (though this was the basis of his classification), but kept in mind and combined all their other—chemical—properties.

In Mendeleev's time, 63 elements were known. In the table he drew up in 1869, only 36 of them complied with the principle of increasing atomic weights. This principle had been violated for 20 elements, and on the basis of his table Mendeleev corrected the atomic weights of the remaining 7. He was so sure of the system he had found that he predicted the properties of several hitherto unknown elements and left gaps for them in his table. Indeed, these elements were discovered soon afterwards: scandium, No. 21 in 1875, gallium, No. 31 in 1879, germanium, No. 32 in 1886, rhenium, No. 75 in 1925, and technetium, No. 43 was synthesized only in 1937.

Strictly speaking, we must admit that Mendeleev discovered his system in spite of the facts, rather than

on their basis. It was as if he could visualize the table beforehand, and took into account only the facts that did not contradict it in any way. As in a "Find the Hidden Hunter!" picture puzzle, Mendeleev suddenly saw the clear-cut outline of the required picture in the midst of the confused conglomeration of lines. Once it has been discerned, it is impossible to pay no further heed to it, even if one makes a great effort. (This trait of human psychology is well known.) At this point, Mendeleev displayed the phase of his intellect that distinguishes a genius from a talented person. This was his exceptional intuition, a rare gift of nature that enables one to see the truth through the husk of false facts.

Mendeleev's periodic table of elements put an end to the ancient controversy between the conceptions of Aristotle and Democritus on the nature of elements. An unobservable property of Democritus' atom, its atomic weight (quantity), varies along the horizontal rows of the table. Along the vertical rows the atoms are grouped naturally in families with similar chemical properties, such as valence, the capacity for participating in chemical reactions, etc. These are observable properties (qualities) that affect our sensory organs and are related to the ancient "innate properties" of Aristotle.

Lagrange once said, "Lucky Newton! The system of the universe can be established but once". Mendeleev established the system of the chemical universe. This also can be done only once. That is why his name, like Newton's, will never be forgotten as long as science exists.

EXPLAINING THE TABLE

A question that arises (and always has) when we look at Mendeleev's table is: "What is this, merely

a convenient device for memorizing the elements, or is it a fundamental law of nature?" This table yields much information to the knowing look of a chemist, but all of this is beyond the scope of our tale. We shall try to clarify only the main points: if it is a law of nature, then:

What determines the order in which the elements are arranged in the table?

What is the cause of the periodicity of their properties?

What does the length of the periods depend on?

Attempts were made to answer these questions for half a century—from Mendeleev to Pauli. The table of elements was rewritten many times, cut up into various pieces and then glued together again on a plane surface and on three-dimensional figures in all possible and some impossible ways. But, as always, the cause of the phenomenon lay outside of it: the table could be explained only by physics and only after the theory of the atom had been founded.

As we have seen, Mendeleev knew, when he devised his table, that the atomic weight only approximately determines the place of an element. Nevertheless, by some method known only to him, he did manage to position the elements properly in his table. After this it was quite easy to number them successively. But has such a numeration any deep-seated implications? We could equally well number the blocks of our toy picture puzzle, and then quickly and easily restore the whole picture each time we disarrange the blocks. This, of course, may be convenient, but has no particular significance because the numbers on the blocks are in no way related to the piece of the picture painted on them.

Does a deep intrinsic relationship exist between the chemical properties of an element and its *ordinal*

number (atomic number) in the table? Or is this an external and arbitrary feature like the numbers of the houses along a street? If this was actually so, it would have been necessary to change all the subsequent numbers each time a new element was discovered, as it is necessary to change the house numbers in a block each time a new building is erected (assuming, of course, that the civil authorities are too improvident to foresee such a possibility). In short, what is the ordinal number of an element? Is it a convenient means of finding it in the table, or is an *intrinsic* characteristic, inherent in the element and independent of any tables? History is inclined to favour the latter assumption: in the hundred years elapsed since the table was founded, not a single change has been made in the numbers of the elements.

The reason why the table has such stability was discovered only after Rutherford's investigations. In 1911, just after Rutherford published his paper on the planetary model of the atom, the Dutch physicist Antonius van den Broek wrote a short article for a German journal in which he made the assumption that *the (atomic) number of an element in Mendeleev's table is equal to the nuclear charge of its atoms.*

In two years time, when studying the X-ray spectra of various elements, this hypothesis was proven by one of Rutherford's most brilliant assistants, Henry Gwyn-Jeffreys Moseley (1887-1915). Moseley's work became the main event in physics even in those years so full of discoveries. He did not complete his investigations, he was killed on August 10, 1915, on the Gallipoli peninsula during the Dardanelles campaign of the First World War. On that sunny beach in Greece, the great physicist in the uniform of a liaison officer of a British field-engineer company fell a victim to the madness that had seized the whole world.

What were the essence and importance of his discoveries?

First, that the elements were correctly arranged in the table.

Secondly, that *all the elements had already been discovered* with the exception of those for which gaps had been left in the table.

Such finality of any statement is an unaccountably attractive feature. It can be especially appreciated when we are dealing with a system of the universe. Moseley's work had put the final touches to the establishment of a system of chemical elements. It only remained to understand the why and how of the matter.

Nature took pains to conceal its main properties as far away as possible from the eyes of scientists: the nuclear charge of the atom is reliably enclosed by a coat of electrons and is inaccessible for measurement by any chemical and most physical methods. This property of atoms was discovered only after they were bombarded by such missiles as alpha particles. At the same time, it is precisely this well-hidden property that determines the structure of atoms and all the observable properties of elements consisting of these atoms. If we really wish to be intimate with the atom, we must first get to its nucleus. (As in the Russian fairy tale about Kashchey the Immortal: high on the mountain there grows an oak, on the oak there is a chest, in the chest there is a hare, in the hare there is a duck, in the duck there is an egg, in the egg there is a needle, and at the point of the needle is the death of Kashchey.)

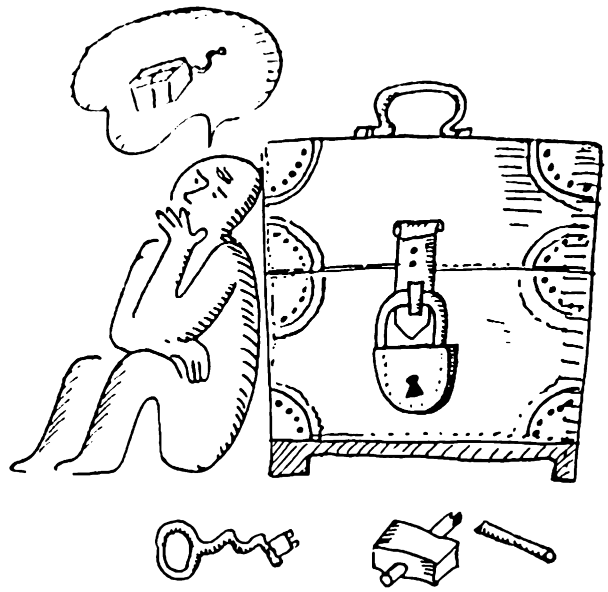
Owing to some profound causes, which we do not fully understand yet, the nuclear charge of the atom is approximately one half of its atomic weight. Hence, if we arrange the elements in the order of increasing

atomic weights, we thereby align them more or less in the order of the increasing nuclear charges of their atoms. Mendeleev, of course, was not aware of the existence of nuclei, but he sensed that atoms have some kind of additional property, more fundamental than the atomic weight. Therefore, in arranging the elements in his table, he had more confidence in his intuition than in the atomic weights. It was as if he had peeked under the electron shell of the atoms, counted the number of positive charges in the nucleus and then assigned this number to the element, calling it the number of the element, or atomic number. Obviously, the atomic number is an intrinsic characteristic of an element, and does not depend on our will in this matter, as do the house numbers on a street. (To continue our analogy with the toy picture puzzle, we can say that actually all the blocks turned out to be numbered beforehand. Only the numbers were concealed inside the blocks.)

Finally, we can give a precise definition of an element.

An element is a substance consisting of atoms with the same nuclear charge.

One more question remains to be cleared up. Why does a *monotone variation* of the nuclear charge of atoms lead to *periodic* changes in their chemical properties? Not only chemical, but also physical properties, such as the specific gravity, hardness, and even the state of aggregation, may be changed. For example, elements with the atomic numbers 2, 10, 18 and 36 are the gases helium, neon, argon and krypton, which are said to be noble because they are chemically inert and incapable of combining with other elements in ordinary reactions. But if the nuclear charge of these atoms is increased by only one unit, we obtain elements 3, 11, 19 and 37, which are the alkali metals lith-



ium, sodium, potassium and rubidium that in no way resemble the adjacent gases, neither in their chemical nor physical properties. For instance, sodium and potassium so actively combine with other elements in chemical reactions that they cannot be kept in the open air because they are spontaneously inflammable.

Evidently, the reason for the periodic changes in the properties of elements should be sought for in the surrounding electronic cloud and not in the nucleus. The first idea that comes to mind is that the electrons do not surround the nucleus at random, but are arranged in layers or shells. The beginning of the filling up of a new shell coincides with the beginning of a new period, and exactly at this moment the chemical properties of the elements change with a jump. After Bohr's investigations such an idea seemed quite natural, and he was the first to propose it.

The cited observations, however, do not suggest a method for calculating the length of the periods. At first glance, the length of the periods in the table would seem to vary quite capriciously: two elements in period 1, eight each in periods 2 and 3, eighteen

each in periods 4 and 5, and thirty-two in period 6. But as far back as 1906, Johannes Robert Rydberg noticed that the series of numbers 2, 8, 18 and 32 obeys a simple formula: $2n^2$. This regularity could be explained only in 1924 by Pauli after he discovered his exclusion principle.

Pauli's reasoning is easy to follow. As a matter of fact, the motion of the electron in an atom is described by four quantum numbers, which we dealt with in detail in the preceding chapter and which we repeat once more:

n—principal quantum number which can have the values 1, 2, 3, ...;

l—orbital quantum number which, for a given n, can have the values 0, 1, 2, ..., $(n-1)$;

m—magnetic quantum number which, for given n and l, can have the series of values $-l$, $-(l-1)$, ..., -1, 0, 1, ..., $(l-1)$, l, i.e. $2l+1$ values in all;

S—spin quantum number which can have the values $+{}^1/_2$ and $-{}^1/_2$.

Pauli's exclusion principle states that

no two electrons in a given atom can have all four quantum numbers identical.

Therefore, in a shell with the ordinal number n there can be only a restricted number of electrons. For example, the first shell can contain only two electrons. The reason is that when the principal quantum number $n=1$, the orbital quantum number can have only one value $l=0$. Consequently, the magnetic quantum number is $m=0$ as well. The spin of the electron does not depend upon the other quantum numbers and can have the two values: $S={}^1/_2$ and $S=-{}^1/_2$. Accordingly, the first quantum level can contain only two electrons with the quantum numbers: ($n=1$, $l=0$, $m=0$ and $S={}^1/_2$) and ($n=1$, $l=0$, $m=0$ and $S=-{}^1/_2$). Reasoning along the same lines, we can find that eight

electrons are contained in the second shell, eighteen in the third and, in general, a shell with the principal quantum number n contains $2n^2$ electrons. Thus, the number of electrons in the filled shells of the atoms equals the length of the periods of Mendeleev's table.

To visualize more clearly the reason for these numbers, imagine that you are to supervise the occupation of a new block of apartment houses. There are n houses in the block and they are numbered as follows: $l=0, 1, 2, 3, \ldots$ and $(n-1)$. A house with the number l has only $(2l+1)$ apartments. Then, if it is forbidden to move more than two tenants into each apartment, you will find that the whole block can accommodate only $2n^2$ tenants and no more.

Each period in Mendeleev's table begins with an alkali metal and ends with an inert gas. The chemical properties of these metals differ sharply. Now we can readily understand the reason why. The inert gases helium, neon, argon, etc., differ from all the other elements in that their shells are completely filled.

The atoms of the alkali metals, following the inert gases in the table, each contain one electron in the next higher shell. The bonds of these electrons with the nucleus are much weaker than in other atoms. Consequently, the atoms of alkali metals readily lose these electrons and become positive singly charged ions:

$$Li^+, Na^+, K^+, \text{etc.}$$

On the contrary, the atoms of fluorine, chlorine, bromine, etc. lack one electron to fill the outer shell to that of an inert gas. This is why the halogens, as these elements are called, so willingly attach an electron and form the negative ions, F^-, Cl^-, Br^-, etc. When the atoms of sodium and chlorine meet, sodium yields its outer electron to chlorine, and the ions

Na^+ and Cl^- are formed. These ions attract each other, forming the molecule NaCl, of which the well-known ordinary salt consists.

In passing, we managed to clear up the meaning of the concept of *valence*, which is so difficult to define chemically. The valency of an element in a compound is the number of electrons of its atom that participate in the formation of a chemical bond. It can readily be seen that the valency, together with other chemical properties, should be repeated periodically after 2, 8, 18 or 32 elements, as each successive shell begins to be filled.

Scientists of the nineteenth century were perplexed by the special properties of the numbers 2, 8, 18 and 32, and called them "magic numbers". They tried to explain these properties in many ways. Some recalled, for example, that an octahedron is the strongest of the polyhedrons, and that in Hindu philosophy there is a teaching concerning the eightfold paths of Buddhism. It is hardly probable that anybody supposed that they could be explained so simply and rationally.

If Dalton, Lavoisier, Mendeleev and others, who devoted their lives and energy to a study of the system of chemical elements, could visit our times, even for a short while, they would evidently experience the perfect joy of pure knowledge that has at last been attained in the study of the elements. Instead of a random set of substances, some of which may have been mixtures and not elements, they would now see an orderly hierarchy of atoms, ranging from hydrogen to kurchatovium.

We owe this harmony to quantum mechanics, with which we shall now make our acquaintance.

ROUND AND ABOUT THE QUANTUM

ATOMS, NUCLEI AND ISOTOPES

God, in creating all the beasts and birds and fishes in their complete form on the fifth day of Creation, most likely know nothing whatsoever about atoms, or did not wish to go into such details. But had he wanted to begin by first creating all the atoms, the simplest procedure would be the one proposed by William Prout: to build them all of hydrogen atoms.

It is clear, however, that two nuclei of hydrogen (protons) repel each other when they approach near enough. To overcome this difficulty, nature invented another type of particle, neutrons, which, together with protons, can form stable nuclei.

A neutron has zero charge and its mass is almost exactly the same as that of the proton. If two protons and two neutrons are joined together, they form the exceptionally stable nucleus of helium (the same alpha particles that Rutherford employed in his experiments). An atom of helium is evidently four times as heavy as an atom of hydrogen and its atomic weight is therefore 4. The two electrons of helium occupy the innermost shell with the quantum numbers $n=1$, $l=0$, $m=0$, and $S=+{}^1/_2$ and $-{}^1/_2$.

If we add to the nucleus of helium one more proton and one more neutron, we obtain a nucleus of lithium with an atomic weight of 6. There is no more room for the third electron of lithium in the first shell and it occupies the next one with the quantum number $n=2$. This is precisely why the next period of Mendeleev's table begins with lithium. The shell with $n=2$ can hold up to $2n^2=8$ electrons (two electrons on the orbit $n=2$ and $l=0$, and six electrons $n=2$, $l=1$ and $m=-1, 0$ and 1). By gradually adding protons

and neutrons to the nucleus of lithium, and electrons to its shell, we can consecutively build up the whole second period, from lithium to neon.

Here, for the first time, we run into a new phenomenon. We know for sure that we must add five protons to the nucleus of lithium to obtain an oxygen nucleus, because the nuclear charge of lithium equals three and that of oxygen equals eight. But how many neutrons should we add? Sometimes five, we find, and sometimes seven. Accordingly, the atomic weight of oxygen is sometimes 16 and sometimes 18. But what, in such a case, does the word "oxygen" mean? Is it the oxygen that we breathe? Now we know that it is a natural mixture of isotopes of oxygen with the atomic weights 16 and 18, which was once formed in nature and cannot be separated by any chemical means whatsoever. The chemical properties of elements depend solely on the nuclear charge of their atoms and the structural features of their electron cloud rather than on their atomic weight. (Only now can we really appreciate the profundity of Mendeleev's reasoning. He regarded the concept of atomic weight with due respect and also with great caution and, in arranging the elements in the table, put more trust in his intuition than in the natural order of atomic weights.)

The term *isotopes* was coined by Frederick Soddy in 1913. It is derived from the Greek and means "having the same place", that is they occupy the same place in Mendeleev's table. It was found that several isotopes of each element, sometimes very many, exist in nature. For example, hydrogen has four and iron has ten.

Tin and lead have the most of all: twenty-six isotopes each. All in all, about one and a half thousand isotopes of various elements are found in nature.

After the discovery of isotopes, physicists began

to make a distinction between "pure" and "mixed" elements.

A "pure element" is a substance consisting of only one kind of atoms, all having the same nuclear charge and the same mass. Such an element can be denoted by the symbol, for example, $_8O^{16}$. This means oxygen with a nuclear charge of 8 and an atomic weight of 16. A "mixed element", which is the same thing as an ordinary chemical element, is simply a natural mixture of "pure elements".

When isotopes were discovered, a new problem arose. How should atomic weights be measured? With the weight of what element should they be compared? It was found to be inconvenient to compare them with the weight of hydrogen any longer and so the carbon scale was adopted in 1961 which is used all over the world. It defines the new atomic mass unit (amu) as $^1/_{12}$ of the mass of one atom of the carbon isotope $_6C^{12}$.

Owing to the investigations of Francis William Aston (1877-1945) and many others, we are able now to measure atomic weights to great accuracy. For example, in the carbon scale, the atomic weight of hydrogen $_1H^1$ equals 1.00782503 amu.

Whether an element is "pure" or "mixed" is all the same to chemistry. It cannot tell them apart even with the finest and most precise methods of analysis. All the more unattainable is this for the imperfect human senses. But sometimes this difference becomes evident to everybody and disastrous to many. The survivors of the Japanese cities of Hiroshima and Nagasaki will remember till their dying day the difference between the harmless isotopes of uranium and the isotope $_{92}U^{235}$ with which the first A-bombs were filled.

By chance or otherwise, but there were many interesting people among the scientists that established the system of elements.

Robert Boyle (1627-1691) was an outstanding person. He was deeply influenced by the philosophy of Francis Bacon and his teaching on experiment being the principal measure of truth. This may be why Boyle established one of the first quantitative laws of physics, known now as Boyle's (or the Boyle-Mariotte) gas law. It is a curious fact that in the manner of his work, Boyle is much closer to our day than to his own. He did not write scientific papers, he dictated them to his secretary; he did not do his experiments himself, he assigned this work to his assistant (who, to his good fortune, happened to be the subsequently famous Robert Hooke).

Boyle was the fourteenth child and the seventh son in a rich family. From childhood he suffered from kidney stones. To some extent this may have influenced his mode of living. He never married, was devoutly religious, and friends who knew him over forty years said that he never mentioned God without making a reverential pause. For 16 years (1661-1677) he was the director of the noted East India Company, and in this capacity his chief concern was the activities of the missionaries in the colonies. About one third of his learned works were devoted to theology. He personally financed the translation of the Bible into the Turkish, Arabian and Malayan, and even into the languages of the American Indians.

At the same time, Boyle was one of the founders of the Royal Society and served in its first council.

Boyle was a tall, lean man and, towards the end of his life, pallid and wasted away. Though he was weal-

thy and of high station, he lived a very simple life; he was disciplined, gentle and exceptionally polite. He was offered a peerage in 1680, but he declined it because his conscience would not allow him to take the oath required upon such an occasion. Boyle died in bed as he was correcting the proofs of his *Essay on the General History of the Air*.

John Dalton was born on September 5, 1766, in the family of a poor weaver of Cumberland County in the north of England. When the time came he was sent to school in a nearby town. In his twelfth year, after the schoolmaster resigned, Dalton reopened the school first in his home and later in a Friends' Meeting House of the village, and taught there for the next two years. This fact in itself is certainly extraordinary, to say the least, but no comments or recollections of his contemporaries have reached us.

After a year of farming, at the age of fifteen, he left home and joined his elder brother Jonathan. During the next twelve years Dalton taught in this school until in 1793 he was offered the post of a tutor in mathematics and physics at the New College in Manchester. He taught there for six more years, soon joining the Manchester Literary and Philosophical Society where he read scientific papers from time to time. His first paper was on colour blindness (he had the red-green type) which is now called Daltonism.

He lived the rest of his life in Manchester and died July 27, 1844, after having been paralysed for the last seven years.

Dalton's antecedents were Quakers, members of the Society of Friends, one of the strictest of the protestant religious sects. This circumstance, perhaps, augmented his natural traits. He lived a deliberate life; his day was never varied. His neighbours could tell the time within a minute when he took outdoor ob-

servations on his thermometer and barometer. He finished his workday at nine o'clock in the evening and, after having his dinner, would sit quietly with his family, smoking his pipe. He would seldom speak, making only a brief remark from time to time.

Every Thursday, in the afternoon, he would stop working and walk to a bowling green alongside the Dog and Partridge Tavern. Here he would drop his sober and deliberate manner, and, to the surprise of the onlookers, he would wave his arms excitedly and bowl the ball with unexpected enthusiasm. He would make a few careful wagers always precisely set down. The day ended with tea and a pipeful of his favourite tobacco. Then he would return home to begin his evening meteorological observations. On Sundays, in Quaker dress—knee breeches, grey stockings and buckled shoes—he would twice attend the public prayer meetings, although he never discussed his religious views publicly.

Dalton read very little and frequently boasted that he could carry his library on his back and had not read half the books. One of his biographers wrote of him that like all self-educated persons, the desire to know what had been accomplished by others was less developed in him than his firm belief in the accuracy of what he himself had discovered.

Some of his traits aroused a feeling of aversion in many of his contemporaries. Sir Humphry Davy's brother, Dr. Davy, a meteorologist, recalled in later years that "his aspect and manner were repulsive ... his voice harsh and brawling, his gait stiff and awkward".

He made approximately the same impression on his fellow members of the Literary and Philosophical Society, but nevertheless they elected him to be their president in 1817 in recognition of his outstanding scien-

tific achievements. Towards the end of his life, his services to science were universally acknowledged. In 1822, he was elected a regular member of the Royal Society, and in 1830 the French Academy elected him as one of its eight foreign associates, in place of Sir Humphry Davy who had died the previous year.

As always in such cases, subsequent generations were and are completely indifferent to the personal shortcomings of a scientist. They remember only what was best in him: his ideas. Evidently, in this lies one of the reasons for the advancement of mankind through the ages.

Antonius van den Broek (1870-1926) was a lawyer and could devote only his spare time to science. This itself is a rarity in our twentieth century, and van den Broek was a remarkable person in all other respects as well. He was profoundly interested in science; he did not like scientific meetings and discussions; his philosophical credo had made him a vegetarian; and his dress, and especially the sandals he wore, obviously belonged to a different age.

When Rutherford was told of van den Broek's atomic number hypothesis, he became very irritated and said that "only a layman should publish a lot of guesses for fun without sufficient foundation". Traces of this hostility remained for a long time. Even many years later, Rutherford persistently expressed his dissatisfaction when Bohr made reference to van den Broek in his works on atomic theory.

Part Two
Ideas

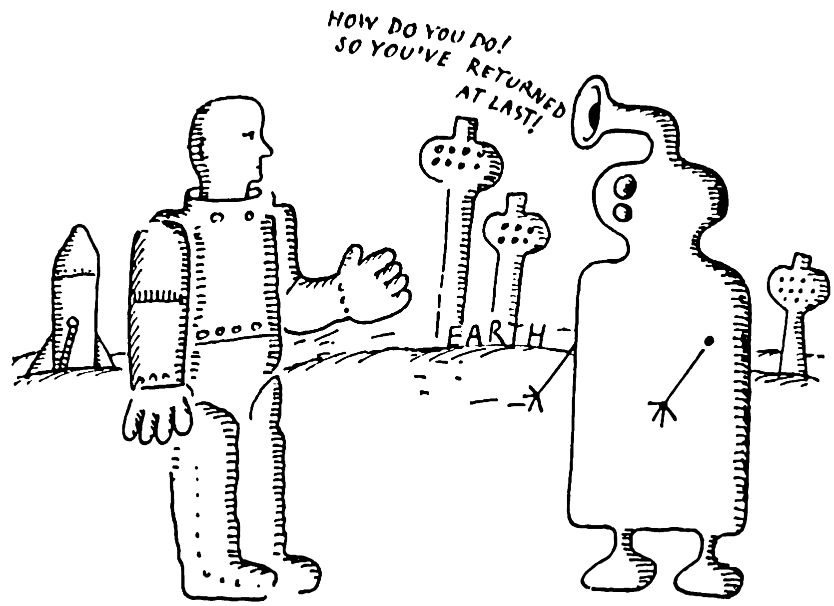
Chapter Six

CONTEMPORARIES COMMENT ON BOHR'S THEORY * PHENOMENON, IMAGE, CONCEPT, FORMULA * HEISENBERG'S ATOMIC MECHANICS

The time will come, before the end of our century, when billions of TV screens, all over the world, will feature a live broadcast of the return of our astronauts from their first flight to Mars. They will bring back tons of film and samples of Martian rock and soil. But not these items will be the most prized of their trophies. Such things can be brought back to earth by robots on unmanned spacecraft. The astronauts will return with their *impressions*. It will be very difficult for them to share these impressions, primarily because none of the terrestrial languages has words that exactly correspond to all the things that struck them most.

They will probably manage, during the long homeward flight, to cope with this difficulty among themselves. Recalling their recent impressions, they will have to invent new words for them, or new combinations of words, otherwise they will not be able to come to any understanding.

The real difficulties will begin later, after their return to the earth, when they try to relate their im-



pressions to somebody else. Everybody who did not make the flight with them will understand their words as before, with their habitual terrestrial meaning. Much time will pass before their audiences master all the new words and give them the same meaning that the astronauts do.

That is the way it always happens—in science and in art, in engineering and in politics. The meaning of words is determined by tradition and by custom, but their connotation only becomes clear from their context. Man discovers new phenomena and refers to them with old words but puts a different meaning into them, one that can only be understood if you know the origin of the new concepts and their relationships with the previous ones.

This tendency to distinguish the needed meanings of words from the customary ones leads to the emergence of a scientific jargon which induces quite natural resentment in editors. Amateurs in science run to the other extreme; they accept all its statements literally and remain unaware of the complex system of conventions that each assertion of science is surround-

ed by. This quite often leads to misunderstandings which amuse physicists and distress the amateurs.

At the turn of the century, physicists discovered a new world, the world of the atom. They were stunned by the wealth of new phenomena, forms and laws governing these phenomena. They hastily invented names for them but were not quite sure as to their exact meaning. In their effort to avoid ambiguity, many scientists stopped trusting words at all; they believed only equations. These were vague times in physics, when the principal facts were acquired that have nourished the science of the atom to this day. Up till now, in our quest, we have tried to discuss as many of such facts as possible. Now we shall try to find words that will impart the proper meaning to these facts.

We began our tale about quantum mechanics with the definition: quantum mechanics is the science of the structure and properties of atomic objects and phenomena. From the very start we found that we were unable to define the concept of an "atom". We still cannot define it entirely uniquely, although we now know much more about it than in the beginning. In Part One we retraced in detail how experiments gradually changed speculative images into a more complex, less visualizable, and yet more authentic picture of the atom.

At the beginning of this century, you could no longer find a physicist who conceived of atoms as tiny hard spheres. Nothing remained of Democritus' initial conception of the atom except the idea that a limit exists to the divisibility of matter in nature. After this limit, matter is transformed into a new quality.

Little by little scientists proved that the atom does exist but in no way does it resemble the atom of Democritus. They discovered that the atom consists of a nucleus and electrons. They learned that it emits

rays. And they established that this radiation is related to the motion of the electrons in the atom. It then became necessary to find the *laws* of this motion. At this point, quantum mechanics was devised.

Its development was begun by Niels Bohr. He was the first to realize that Planck's constant h is not an amusing hypothesis helping to explain the black-body spectrum, but a physical reality that must be taken into account in explaining *all* atomic phenomena. On the basis of this idea, Bohr formulated his famed postulates on the *stationary state* and the *quantum jump*. Bohr's postulates contradicted all previous ideas in physics, but introduced unexpected order in the primeval chaos of experimental facts.

But science takes nothing for granted, even Bohr's postulates. They either had to be rejected, or their contradictions had to be eliminated. Our next chapters will be devoted to the story of how physicists succeeded in solving this problem and how a consistent theory of atomic phenomena was devised.

CONTEMPORARIES COMMENT ON BOHR'S THEORY

In 1949, Albert Einstein wrote about the period in which quantum mechanics was founded:

"All my attempts to adapt the theoretical foundations of physics to the new facts were completely unsuccessful. It was exactly as if the ground was slipping away from under our feet and we had no firm soil that we could build on. It always seemed a miracle to me that this vacillating and quite contradictory basis turned out sufficient to enable Bohr—a man of brilliant intuition and keen perceptibility—to find the predominant laws of spectral lines and the electron shells of atoms, including their significance for che-

mistry. This still seems to be a miracle to me. It is a manifestation of the highest form of musicality in the realm of thought."

It is always easier and safer to assess the significance of a discovery from a distance. This task is much more difficult for contemporaries. Their knowledge is as yet insufficient to distinguish the merits of a new theory from its shortcomings. Notwithstanding all the successes of Bohr's theory, his contemporaries were extremely discontented.

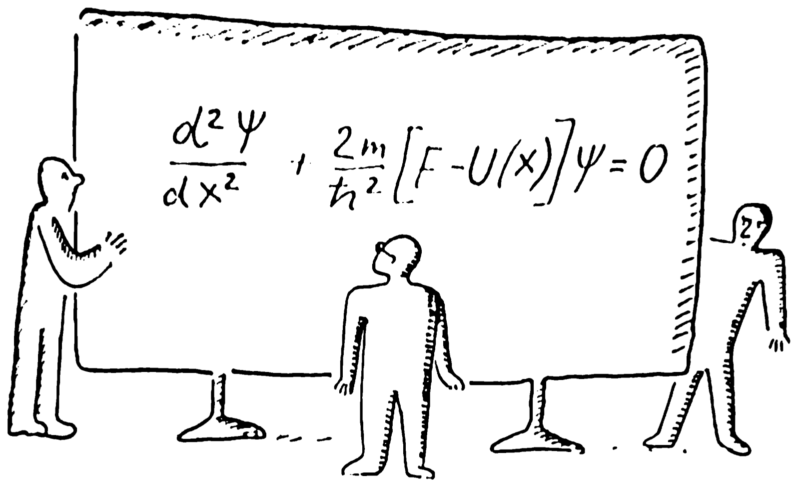
What they wrote and said at that time is both unusual and instructive to us now.

"If this is correct, it signifies the end of physics as a science" (Albert Einstein, 1913).

"The atom exists eternally. This we know beyond question. But do we understand this? No, we do not. And we conceal our lack of understanding by the likewise incomprehensible quantum conditions. The process of radiation is an act of regeneration of a demolished atom. Its mechanism is not understood by us. And again we conceal our lack of understanding by an incomprehensible quantum condition, Bohr's second hypothesis .... The whole method proposed by Bohr is based on quantization, which is a stone-blind, scarcely logical way of reasoning. It is based on what could be expressed as formal intuition" (Dmitry Sergeevich Rozhdestvensky, 1919).

"The theory of quanta is similar to other victories in science; for some months you smile at it, and then for years you weep" (Hendrik Anthony Kramers, 1920).

"In their present form, the quantization laws are, to a certain extent, of a theological nature, entirely unacceptable to a naturalist. Thus, many scientists are rightfully indignant with these *Bauern-Regeln* (peasant laws)" (Paul Sophus Epstein, 1922).



"We are immeasurably far from such a description of the atomic mechanism that would allow us to retrace, for instance, all the motions of the electron in the atom or to understand the role of the stationary states....

"...The theory of quanta can be likened to a medicine that cures the disease but kills the patient" (H. A. Kramers and Gilles Holst, 1923).

"Physics has run into a blind alley again. In any case, it has become too difficult for me, and I would prefer to be a comedian in the cinema or something similar and hear no more about physics" (Wolfgang Pauli, May 21, 1925).

Even Bohr himself had a "feeling of melancholy and hopelessness" in those days.

This unanimous discontent is incomprehensible to anyone unacquainted with the structure and methods of modern physics. To realize the cause of such dissatisfaction, it is necessary to get some idea, at least in outline, of the intrinsic logic of natural sciences. This may be an unusual business for some and hardly a simple one, but it is absolutely necessary for an understanding of quantum mechanics.

What strikes a layman in a textbook on quantum mechanics is the abundance of formulas and equations. Quite soon he finds, however, that this is a necessary,

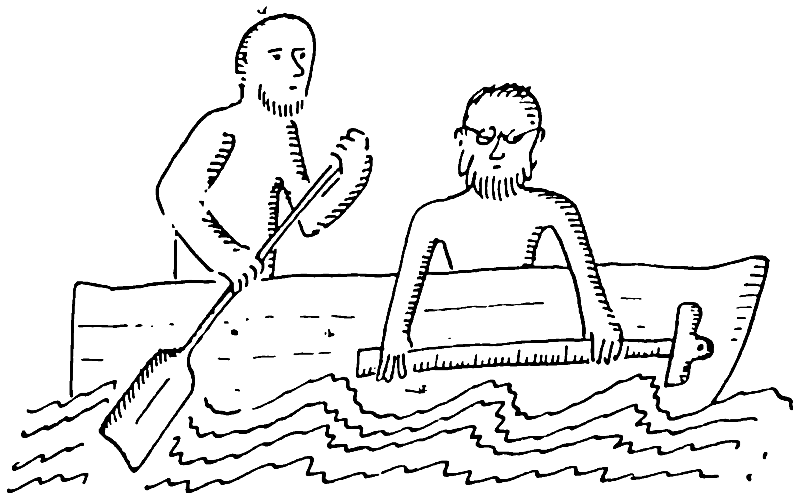
but not the most difficult part of the science of the atom. Much more complicated is to comprehend *what* is hidden behind the formulas or, as it is customary to say in physics, "to understand the physical meaning of the formulas". These difficulties should not be exaggerated but, since they do exist, it may prove helpful to keep them in mind. The point is that many words that we have been accustomed to from childhood are used in an unusual sense in quantum mechanics.

PHENOMENON, IMAGE, CONCEPT, FORMULA

Any knowledge of nature begins with our senses. A child touches his wooden horse with his fingers, listens to his mother's voice, and sucks her breast. In short, from the very first days of his life he finds himself in a world of *phenomena* which give rise to *images*. He has, as yet, no names for these phenomena and images. Only gradually does he begin to recognize *words* corresponding to them, and learns to understand what images are hidden behind the words of other people. Quite soon he begins to realize that the same words give rise to different images in different persons. Finally, he finds that there are words (or groups of words) that are not linked directly with images, though they are begotten by them. These are *concepts*.

Concepts generalize collective experience. They are purposely deprived of details inherent in specific images, and can therefore serve as a means of communication between different people.

As the child develops, he begins to think using concepts. He suddenly understands that a "wooden horse" is only one of his "toys", and that "water" is not necessarily sea water, or water from a river, or water



flowing out of a faucet, but just simply *water*. The capacity for abstraction is the first indication of a grown-up and a necessary condition for the advance of any science.

Concepts, however, are also not completely unambiguous, if only because they give rise to different images in different people. Even in our everyday lives, such ambiguity may lead to misunderstandings, but this is much more dangerous in science because its results claim to have an objective meaning and to be independent of the whims or opinions of any one person or a group of persons. Therefore, each concept in science is associated with a set of symbols and numbers, and strictly definite rules are specified for dealing with these symbols and numbers. Only this leads to the single-valuedness that enables scientists of different countries and generations to communicate with one another.

The linkage:

phenomenon → image → concept → formula

can be schematically depicted and explained by the example of the origin of the concept of a *wave*.

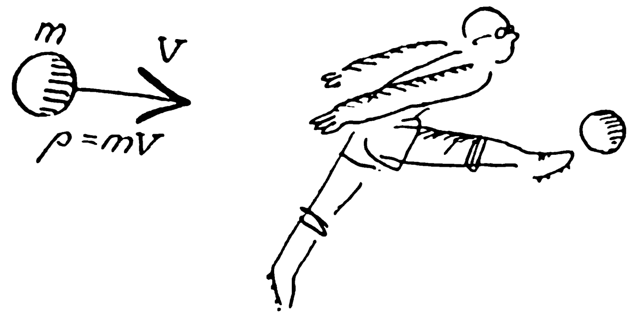
Man observed various phenomena: waves at sea and circles produced by a stone thrown into a pond, the

propagation of light and the vibration of a string. They all gave rise to the formation of images. Gradually, it became clear that all these different phenomena have something in common, namely, they are all associated with some *periodic process* whose characteristic features are the phenomena of interference and diffraction (with which we have already dealt in detail). Thus a new concept—*the wave*—was formed. To make it entirely single-valued, it was associated with four parameters: the amplitude A, velocity of propagation v, wavelength λ and frequency ν.

Likewise the concept of a *particle* does not assume that you will visualize a specific image such as a billiard ball, shot or a dust speck. It is enough for a physicist to know that a particle is a certain object whose internal structure is of no interest to him, but which has a mass m, velocity v, momentum $p = mv$ and a *trajectory of motion* that can be followed by the physicist.

The *trajectory*, or path, is still another new concept that is required to define the concept "motion of the particle". On the face of it, this process is infinite: to define a concept we have to use another concept which again must be defined, etc. But this is far from the case. In physics there exist several primary concepts which can be defined without reference to others, namely by prescribing exact recipes for measuring the quantities which correspond to these concepts. Such concepts are the time t, coordinate x, charge e, etc.

The trajectory of the motion of a particle is specified if at each instant of time t we can indicate the position of the particle in space, i.e. its coordinate x. We must either *measure* the coordinates x at the instants of time t, or *calculate* them. The first problem is solved by experimental physics, the second by theoretical physics. The second problem can be solved,



however, only if we know the *physical laws* according to which the particle travels.

What is a physical law? It is a constant relation between a phenomenon and quantities written by means of mathematical symbols in the form of equations. Each group of phenomena has its own laws of motion. There is one set of laws for mechanics (Newton's equations) and another set for electrodynamics (Maxwell's equations). All of them taken together—concepts, physical laws, the formulas that express them and their consequences, are said to constitute an exact science.

Any completely developed science should be *logically consistent*. This means, in particular, that each concept within the scope of this science can be employed only in a single strictly definite sense. This may be hard to accomplish, but it is unavoidable since scientists, like all other people, communicate with one another by means of words and not through formulas. They require formulas only for the single-valued recording of the results of their investigations.

For some centuries mechanics was cited as an example of a logically completed science whose perfection had earned it the epithet "classical". Mechanics is the science of the mechanical motion of bodies. Its laws are obeyed by almost all the visible movements in nature, whether the fluttering of a butterfly or the motion of planets in space. The classical perfection of mechanics had long been entrancing scientists and

they made attempts to employ it to explain mechanical and even all other forms of motion in nature.

"Everyone unanimously agrees that the aim of physics is to bring all phenomena of nature within the scope of the simple laws of mechanics," wrote Heinrich Hertz as late as 1894, on the threshold of the revolution in physics.

Motion is one of the most complex concepts of physics. The imagination is free to link any images with it, from the rustling of leaves to the charge of an infuriated rhinoceros. Even the most fantastic pictures of motion, however, have something in common: the displacement of certain items in reference to others in the course of time. The concept of motion becomes more definite after introducing the concept of a trajectory, perhaps because it again acquires features of visualizability. Only now this visualizability is of a special kind. The image it calls forth in no way resembles a butterfly or a rhinoceros. Nevertheless, the visualizability associated with the concept of a trajectory is misleading. Frequent repetition of the word-combination "trajectory of motion" eliminates the distinction between the two words in one's mind although they only coincide for mechanical motion. Our training and development is such that it is difficult for us to imagine any other kind of motion except the mechanical kind. Hence, we try to comprehend all other kinds of motion with the same concept of a trajectory. In this we naturally fail, for instance, when we attempt to conceive of electrical motion. You can, of course, picture a high-tension power transmission line or a telephone trunk line, and imagine that the wire is the "trajectory" of the electric signals. Such an image, however, has no practicable purpose; the waves of electric signals are not a liquid flowing through the wires.

It is even more complicated to define the concept of motion in quantum mechanics. Moreover, the day when this concept was first defined consistently can be regarded as the birthday of modern quantum mechanics.

HEISENBERG'S ATOMIC MECHANICS

When the ecstasy over the first successes of Bohr's theory were over, all of a sudden physicists soberly realized the simple truth: Bohr's scheme was contradictory. They could not get away from this fact. This was the reason for Einstein's pessimism of those days, as well as Pauli's despair.

Time and again, physicists found that in its motion in the atom the electron does not obey the laws of electrodynamics. It does not fall into the nucleus nor does it radiate unless the atom is excited. This was all so extraordinary that it could hardly be grasped: the electron, which had "descended" from electrodynamics, suddenly got out of control of its laws. Any attempt to find a logical way out of this vicious circle always led to the same conclusion: Bohr's atom cannot exist.

But our logical constructions are no concern of nature's. Contrary to logic, atoms are stable and, as far as we know, exist eternally. If the laws of electrodynamics cannot ensure stability of the atom, so much the worse for them. This means that the motion of electrons in the atom obeys other laws.

Subsequently, it turned out that Bohr's postulates were fortunate guesses of fundamental laws, then unknown, but which were later named the laws of quantum mechanics.

Quantum mechanics is the science of the motion of electrons in an atom. That's what it was originally

called: atomic mechanics. And it was the fortune of Werner Karl Heisenberg to be the first among those who founded this science.

At the invitation of Bohr, Heisenberg came to Copenhagen in the spring of 1925 from Munich where he had just graduated from the university. He had studied physics under Arnold Sommerfeld of elliptical electron orbit fame. In Denmark, Heisenberg immediately found himself in the midst of heated scientific arguments and among people for whom physics had become their life-work. Half a year passed in work and endless discussions, all about the same things: why doesn't the electron, an object of electrodynamics, obey its laws in the atom, and what is the reason for the surprising power of Bohr's illogical postulates? And finally, what does the very concept of "motion" mean in this case?

Summer came. In June, Heisenberg fell ill and went for a holiday to the island of Heligoland in the North Sea. He did not succeed in getting a rest. All of a sudden, he understood that you cannot conceive of the motion of the electron in an atom as the motion of a tiny sphere along a trajectory. This is impossible because an electron is not a ball but something considerably more complicated, and one cannot follow the motion of this "something" as simply as that of a billiard ball. If this guess is correct, then, in attempting to follow the trajectory of an electron in an atom, we are asking nature illegitimate questions such as those asked in ancient times: "What holds up the earth?", "Where is the end of the world, or the falling-off place?", and later, "Which side of the world is up and which is down?"

Heisenberg contended that the equations, by means of which physicists intended to describe motion in the atom, must contain no quantities except those

that can be measured experimentally. Experiments demonstrated that the atom is stable, that it consists of a nucleus and electrons, and that it can emit rays if its state of equilibrium is disturbed. These rays have a strictly definite wavelength and, if Bohr was to be believed, they are emitted when an electron jumps from one stationary orbit to another. Bohr's scheme, however, gave no indication about what happened to the electron during the jump or, so to say, in its "flight" between the two stationary states. From force of habit, all physicists, including Heisenberg, were making every effort to find the answer to precisely this question. But, at some instant, it struck him that the electron just never happens to be "between" stationary states; it simply does not possess such a property!

And what was there? There was something that he did not as yet know how to call, but was sure that it should depend only on *to where* and *from where* the electron jumps.

Until then, physicists had been trying, on the basis of the equations of electrodynamics, to find the hypothetical trajectory of the electron in the atom as one that continuously depended on time, and for which a series of numbers, x_1, x_2, x_3, ..., could be specified which marked the position of the electron at the instants of time, t_1, t_2, t_3, ... Heisenberg maintained that there was no such trajectory in the atom and that, instead of a continuous curve $X(t)$, there was a set of discrete numbers X_{nk} whose values depended upon the numbers n and k of the initial and final states of the electron.

This important and quite complicated statement can be illustrated by a simple analogy. Assume that you have a chessboard before you, and that a fly is walking over it. If you wish, you can trace its path

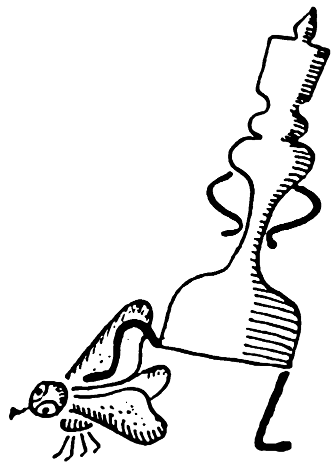
in great detail by recording its position x at each instant of time t. From these measurements you can then readily plot the curve $X(t)$, i.e. the trajectory of the fly's motion. You can, of course, reduce the amount of data to be recorded by merely writing down the squares through which the fly passed. This also provides information on its displacement but one can easily grasp that such a description will be incomplete from the viewpoint of classical mechanics.

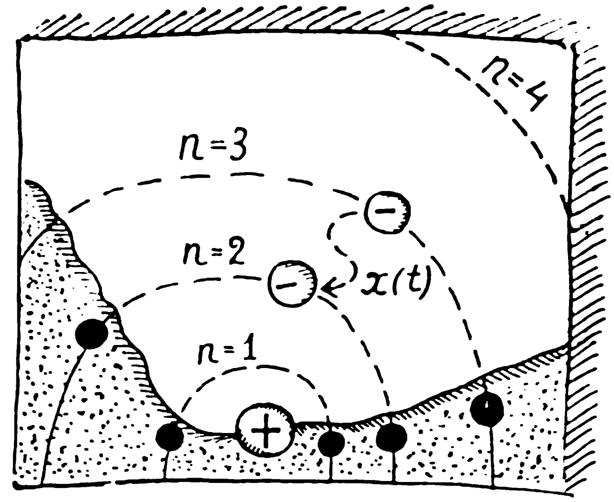
Now assume that you are playing chess on the same board and have decided to make the traditional first move e2—e4. Here, the results of your move do not depend at all along what path you have moved the pawn. This is obvious; the rules of chess do not depend upon the laws of mechanics and, consequently, do not require the concept of a trajectory.

Heisenberg reasoned out that the "rules of the atomic game" do not require any knowledge of any trajectory either. Accordingly, he conceived of the state of the atom as being an infinite chessboard in each square of which a number X_{nk} is written. Naturally, the value of these numbers depends upon the location of the square on the "atomic board", i.e. on the number n of the line (initial state) and the number k of the column (final state) at whose intersection the number X_{nk} is located.

Nobody is surprised by the fact that a play-by-play record of a chess game enables it to be repeated any time, even many years later. Of course, such a record includes no data on how long the game took to play, what emotions the chess players experienced and exactly how they moved the pawns and other chessmen. But all this is of no importance if what interests us is the game itself.

In precisely the same way, if we know the numbers X_{nk}, this distinctive record of our "atomic game",



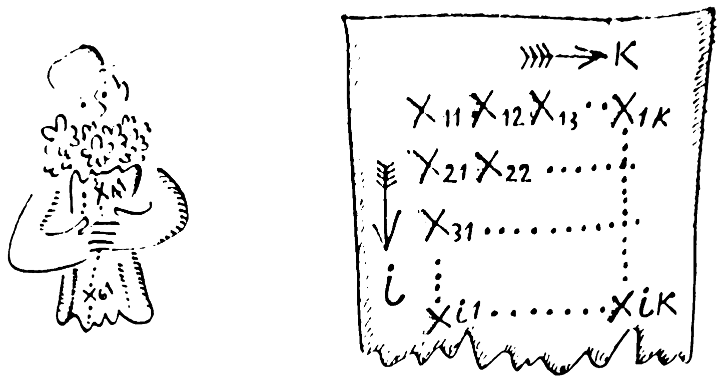


we know quite enough about an atom to predict its observable properties: its spectrum, the intensity of the spectral lines, the number and velocity of electrons that are ejected from an atom by ultraviolet rays, and much more.

The numbers X_{nk} cannot be called the coordinates of the electron in an atom. They substitute for them or, as they began to say later, *represent* them. But even Heisenberg didn't understand at first what these words meant.

Indeed, instead of the table of numbers $\{X_{nk}\}$ one can equally well draw anything, for instance, a flower, and assert that it represents the motion of electrons in the atom. But soon, with the aid of Max Born (1882-1970) and Ernst Pascual Jordan (born 1902), it became clear that the table of numbers $\{X_{nk}\}$ is not simply a table; it is a *matrix*.

What does this word mean? Mathematics deals with quantities and symbols, and each symbol can be manipulated according to definite rules. For example, ordinary numbers can be added, subtracted, multiplied or divided by one another, and the result of these procedures does not depend upon the order in which these manipulations are performed: $5+3=$ $=3+5$ and $5\times3=3\times5$.



But mathematics deals with more complicated items as well. These are negative and complex numbers, matrices, etc. Matrices are tables of values of the $\{X_{nk}\}$ type which have strictly definite rules for their addition and multiplication.

In particular, the product of two matrices depends upon the order in which they are multiplied together. Thus

$$\{X_{nk}\} \times \{P_{nk}\} \neq \{P_{nk}\} \times \{X_{nk}\}$$

This rule may seem strange at first, and even suspicious, but it is not at all arbitrary. In essence, it is precisely this rule that distinguishes matrices from other quantities. We have no right to change these rules at our whim; mathematics also has its unyielding laws. These laws, independent of physics or any other science, express all conceivable logical connections in nature in the language of symbols. It cannot be known beforehand whether all these connections will actually be realized.

Mathematicians, of course, knew all about matrices long before Heisenberg, and could use them. It was a complete surprise, however, to find that these strange mathematical tools with their unusual properties correspond to something real in the world of atomic phenomena. The feat of Heisenberg and Born was that they surmounted the psychological barrier,

found a correspondence between the properties of matrices and the features of the motion of electrons in the atom and thereby founded a new, *atomic, quantum, matrix mechanics*. It is atomic, because it describes the motion of electrons in the atom. It is quantum, because the concept of the quantum of action h plays the title role in this description.

It is matrix, because the required mathematical apparatus consists of matrices.

In this new mechanics, each characteristic of the electron—the coordinate x, momentum p and energy E—is associated with the corresponding matrix: $\{X_{n\kappa}\}$, $\{P_{n\kappa}\}$ and $\{E_{n\kappa}\}$. Then the equations of motion, known from classical mechanics, are written for these matrices (and not for ordinary numbers). It was only necessary to see that all the manipulations of the quantities $\{X_{n\kappa}\}$, $\{P_{n\kappa}\}$ and $\{E_{n\kappa}\}$ strictly comply with the rules of matrix mathematics.

But Heisenberg did more than this. He found that the quantum-mechanics matrices of the coordinate $\{X_{n\kappa}\}$ and the momentum $\{P_{n\kappa}\}$ are not just any kind of matrices but only those which conform to the *commutation relation*

$$\{X_{nk}\}\times\{P_{nk}\}-\{P_{nk}\}\times\{X_{nk}\}=i\hbar$$

where $i=\sqrt{-1}$ and $\hbar=\frac{h}{2\pi}$

In the new mechanics, this commutation relation played the same role as Bohr's quantization condition in the old mechanics. In exactly the same way that Bohr's condition distinguished the stationary orbits from a set of all possible ones, Heisenberg's commutation relation selects from the set of matrices only those that are quantum-mechanics ones.

It is no mere coincidence that the Planck constant h is necessarily present both in Bohr's quantization

conditions and in Heisenberg's equations. As we shall see further on, it is an indispensable member of all the equations of quantum mechanics. This, in fact, is a feature that enables these equations to be infallibly distinguished from all others.

The new equations found by Heisenberg resembled neither those of mechanics nor those of electrodynamics, and hence could in no way violate them. From the point of view of the new equations the state of an atom is completely specified if all the numbers X_{nk} or P_{nk} are known, i.e. if the matrix $\{X_{nk}\}$ or $\{P_{nk}\}$ is known. Moreover, the structure of these matrices is such that in the unexcited state the atom does not radiate.

Note that in our discourse we have nowhere mentioned the concept "motion of the electron in the atom". There is simply no more need for it. According to Heisenberg, motion does not mean the travel of the electron-sphere along any orbit around the nucleus.

Motion is the change in the state of the system in time, and is described by the matrices $\{X_{nk}\}$ and $\{P_{nk}\}$.

The question of the stability of atoms automatically lost its significance as soon as physicists ceased to argue about the nature of the motion of the electron in the atom. From the new point of view the electron is at rest in the unexcited atom and therefore should not radiate.

Heisenberg's theory was intrinsically consistent, a feature so lacking in Bohr's scheme. At the same time, it led to results identical with those of Bohr's quantization rules. Moreover, with its aid it finally became possible to show that Planck's hypothesis on the quanta of radiation $E=h\nu$ was a simple and natural consequence of the new mechanics.

We can continue our efforts to give an account of the consequences of Heisenberg's mechanics without

resorting to formulas. This, however, will be just as unnatural as an attempt to retell a musical composition in words.

To perceive the profundity of quantum mechanics, it is necessary to study mathematics, to learn to handle matrices, in a word, to become proficient in the *trade* of a physicist.

There is nothing mystical or inscrutable about matrices. They are considerably easier to master than, for instance, Latin. But, very likely, not simple enough to be learned offhand during a bus ride. Matrix mathematics, like music, has to be specially studied. Otherwise, the unpleasant after-taste of half-baked knowledge will spoil a pleasure that is within anyone's reach: to feel keenly the beauty of the images and the completeness of the concepts of any profound science without resorting to formulas and computations.

Physicists greeted the appearance of Heisenberg's matrix mechanics with great relief: "Heisenberg's mechanics returned my joy of life and my hope. Though it does not solve the riddle, I believe we can move forward again," wrote Wolfgang Pauli on October 9, 1925.

He himself soon justified his faith in the new mechanics. Applying it to the atom of hydrogen, he ob-

tained the same formulas that Niels Bohr had on the basis of his postulates. Of course, new difficulties appeared, but these were only growing pains, and not the hopelessness of a blind alley.

ROUND AND ABOUT THE QUANTUM

THE FOUNDATION OF PHYSICS

The principal concepts of physics, such as *length*, *time*, *mass*, *charge* and others, cannot be defined uniquely by means of *words* for two reasons. In the first place, these are primary concepts and cannot be reduced to simpler ones; in the second, physics is a quantitative science and it is necessary from the very beginning to correlate such concepts with *numbers*. There is only one way to make these concepts unique: to prescribe a precise recipe for measuring the quantities they correspond to.

We have already defined the concept of "length". One metre is a measure of length equal to 1,650,763.73 wavelengths in vacuum of the orange-red line of the spectrum of Kr-86 (the isotope of krypton with the mass number 86). This spectral line, accepted as the length standard, corresponds to the transition of an electron in the krypton atom between the $2p$ and $5d$ levels. One metre thus defined is approximately equal to one ten-millionth of the distance from the equator to the north pole measured along the meridian of Paris, which was initially accepted in 1799 as the length standard.

The unit of mass of one kilogram is defined as the mass of a cylinder of special shape made of a platinum-iridium alloy in 1789 (its height of 39 mm equals the diameter of the base). This mass approximately coin-

cides with that of a litre of distilled water at a temperature of 4 °C.

To define the unit of time, it is necessary to use some stable cyclic process, such as the rotation of the earth about the sun. So, 1 sec = 1/31,556,925.9747 of the tropical year, which is the interval of time between two successive identical positions of the earth with respect to the stars. However, the length of the tropical year is slowly changing (by 0.5 second per century) due to the precession of the earth's axis and other disturbances. For this reason, the tropical year 1900 is specified for the standard or, more precisely, the year that began at 12 o'clock noon on December 31, 1899.

In the course of time it became clear that it is better to base the unit of time, like the unit of length, on spectroscopic measurements, since this is still the most precise branch of physics. In 1967, the Thirteenth General Conference on Weights and Measures redefined the second as the duration of 9,192,631,770 cycles of radiation associated with the transition of an electron between two hyperfine levels of the ground state of the isotope of cesium with the mass number 133 (Cs-133).

Conversion to the atomic standards of length and time was inevitable, not only because spectroscopy is the most precise branch of physics. The point is that atomic standards are exceptionally stable; they depend neither on the temperature, nor the pressure, nor even on some cosmic disaster. This cannot be said of the initially adopted standards. (The standard metre, for instance, is kept under a bell-glass, at constant temperature in a steel cabinet, in a deep vault whose three keys are in the custody of three different officials, and with other precautions taken.) With respect to the second, the matter is even worse. If some celestial

body unexpectedly passes through our solar system, the period of revolution of the earth around the sun will irreversibly change and, with it, the length of the second. Nothing of this kind threatens atomic standards. They are as stable and invariable as the atom itself, on whose properties they are based.

Three quantities—the metre (m), kilogram (kg) and the second (s)—constitute a part of the International System of Units (SI) and are sufficient to describe all kinds of mechanical motion. Electromagnetic theory requires the measurement of two more fundamental quantities: the charge e and velocity of light c. To describe atomic phenomena, we also need to know the value of Planck's constant h.

Founded in 1875 for precisely determining the fundamental physical constants, the International Bureau of Weights and Measures holds a General Conference on Weights and Measures every six years. At these conferences, the conditions under which measurements of standard quantities are to be made, such as temperature, pressure, and altitude above sea level, are stipulated in great detail. The components of the instruments that are to be used for these measurements are likewise carefully specified and described.

One important feature of such measurements is that only in rare cases is it possible to determine one quantity independently of any others. To measure the remaining quantities it is necessary to resort to the laws of physics. For instance, if the velocity v of a particle is constant, it can be determined by measuring the distance Δx that the particle travels during the time Δt. Thus

$$v = \frac{\Delta x}{\Delta t}$$

This is a simple example of the fact that all fundamental constants are interrelated in a certain sense.

There is a whole special branch of physics, quite a complicated one, whose purpose is to determine the complete set of such constants, taking into account at the same time all the available data on their measurement.

But the most difficult question is that of the limits of application of concepts determined by such methods.

It is quite evident that the units of measurement—the metre, kilogram and second—have been selected so that a person can easily picture them since they are commensurable with his own customary dimensions. In fact, one metre is the height of a 5-year-old child, one kilogram is the weight of a big round loaf of bread, and a second is the time between heartbeats. The question is: do these concepts keep their previous meaning when we pass over to very large or to very small distances, masses or intervals of time?

As yet there is no general answer to this question. We had the opportunity to see, however, that as far as the electron is concerned, the concept of size is no longer applicable. In atomic theory (where we had to replace the concept of "motion" with a new one) the previous concepts of "length", "mass" and "time" are still valid. This means that at least the distance 10^{-10} m, mass 10^{-27} kg, and interval of time 10^{-17} s can still be understood in the ordinary sense.

A similar problem arises in astronomy, when we try to comprehend the vast distances to the galaxies and their masses. Very likely, this is even more difficult than in the theory of elementary particles. In fact, no one can assert lightheartedly that he fully realizes the meaning of the words "one billion light years". Formally, everything is extremely clear: this is the distance travelled by a ray of light in 10^9 years, i.e. the distance $10^9 \times 3.15 \times 10^7 \text{s} \times 3 \times 10^8 \text{m/s} = 10^{25}$ m. But how can we grasp or at least sense what

is hidden behind this symbol? As a comparison, we can recall that the distance from the earth to the sun is 1.5×10^{11} m and a ray of light travels this distance in "only" 8 minutes; that the distance to the nearest star, α Centaurus, is 4.35 light years, and to the centre of our Galaxy 30,000 light years. How true are Pascal's words: "Man dangles between two infinities".

THE HISTORY OF THE FIRST METRE

In 1788 and 1789, many French cities addressed a request to the government asking that a common system of measures be introduced to put an end to misdemeanours in trade on these grounds. Charles Maurice de Talleyrand-Perigord, then Bishop of Autun, put this question before the National Assembly. The French Academy of Sciences appointed a committee consisting of Charles de Borda, Joseph Louis Lagrange, Pierre Simon (Marquis de Laplace), Gaspard Monge (Comte de Péluse) and Marie Jean Antoine Nicolas de Caritat (Marquis de Condorcet). This committee recommended that some fraction of the earth's equator or meridian be adopted as the standard unit of length. This had been proposed long before by the geographer Rigobert Bonne. On March 30, 1791, the National Assembly passed a resolution to accept as the metre one ten-millionth part of the quadrant of the terrestrial meridian. Soon after this, Pierre-Francois-André Méchain in Spain and Jean-Baptiste Joseph Delambre in France began to make geodetic measurements on an arc from Dunkirk (France) to Mont-Jouy near Barcelona (Spain).

These were troubled times. The Great French Revolution had begun in 1789 and was still proceeding; Louis XVI had just been beheaded. On the lands of the sans-culottes, where Delambre had to do his work,

many bell towers had been demolished. This made it necessary to build pyramids of boards and to cover them with white unbleached linen for use as targets to take sights on in the survey. But this led to an uprising of the local peasantry because the white colour was a symbol of royalty. It became possible to continue the survey only after sewing blue and red strips as a border to the white linen.

In pious Spain, where Méchain was working, there were plenty of church towers, but the scientists were not allowed to enter them, being accused of blasphemy. Moreover, the population was frightened by the plague and therefore forbade Méchain to travel freely from town to town. They made him wet all his papers with vinegar and created a great many other minor hindrances. Wearied and ill, Méchain sent in his resignation, but died before an answer was received.

His work was continued by members of the Parisian Academy, Dominique Francois Jean Arago and Jean Baptiste Biot who were more fortunate than Méchain; they received aid from the government and were patronized by prominent bishops and even one famous robber chief. When the work was completed Biot returned to France just before the French army invaded Spain. Arago was immediately arrested and thrown into prison on suspicion that it was, of course, he who had arranged signs on the mountain peaks to lead the invaders into Spain. In captivity Arago read Spanish magazines that announced that he had been put to death and that he had faced his executors with fortitude as any good Christian should.

Soon, however, Arago escaped from prison, fled to Algiers and embarked on a ship sailing to Marseilles. But, on the voyage, the ship was captured by Spanish corsairs and again Arago was thrown into one prison after another with a lot of riffraff. Luckily for him,

a certain African potentate had sent a gift of two African tigers to Napoleon on the same ship. When the potentate heard what had happened he threatened Spain with war. The ship was released, the prisoners were set free and they sailed again for Marseilles, but the ship went astray and reached Bougie instead. From here Arago returned again to Algiers and then, with many adventures, travelled on foot through all of Kabylia; he was again captured and threatened with prison, but finally he was permitted to return to France. What is most astonishing is that after these endless adventures, his notes, sewn into his linen, and even his instruments, remained intact and undamaged.

On the basis of the measurements made by Méchain and Delambre, the skilled mechanic Etienne Lenoir made the standard metre that is now so well known. By a law passed on June 25, 1800, this new unit of length was introduced for general use. "Of all the good measures that remain in our memories of the French Revolution, this is the one we had to pay the least for ...," wrote Delambre in his report in 1806.

Chapter Seven

LOUIS DE BROGLIE * MATTER WAVES * OPTICAL-MECHANICAL ANALOGY * SCHRÖDINGER'S WAVE MECHANICS

János Bolyai (1802-1860), a Hungarian officer, discovered non-Euclidean geometry in his 23rd year and was very happy about it until he found out that somewhere on the border between Asia and Europe Nikolai Ivanovich Lobachevsky (1793-1856) had published his work on the same geometry several years earlier. Then Bolyai's life began to resemble a nightmare. It seemed to him that spies were everywhere; he became harsh and suspicious, and blamed everyone, even his father who had devoted his whole life to the same problem. Farkas Bolyai (1775-1856) was not such a genius as his son, but he was more humane and wiser. On his deathbed he said, "Console yourself, my son; when spring comes, all the violets bloom at the same time."

Such a spring came for the science of the atom in 1925. In three years time, this new science, *quantum mechanics*, sprouted, blossomed out and bore its first fruit. From that time on very little has changed in quantum mechanics. Thus, at times, a volcanic island suddenly appears in the midst of the ocean and

then remains unchanged for centuries. All these events, the island in the ocean and the coming of spring are, of course, unexpected only to those who did not observe the subterranean quakes and passed indifferently by the swollen buds. In Part One, we tried to sense the vague tremors, to discern the almost imperceptible flow of the sap which ushered in the spring of quantum mechanics.

It truly came when Werner Heisenberg broke the ice of prejudice that had buried the congealed foundations of physics, infused new life in the *concept of motion* and created the new *matrix mechanics*. This was the first consistent theory of the atom, one that could explain its stability and that physicists had so long been searching for. But then (quite in keeping with the laws of spring!), only four months later, Erwin Schrödinger founded still another mechanics—*wave mechanics*—which explained the structure of the atom equally well though it had no resemblance to matrix mechanics.

Further on we shall find that matrix and wave mechanics are simply different mathematical forms of expressing the equations of the united quantum mechanics, the science of the structure of atoms. But first of all, we must try to understand the essence of wave mechanics and master the simple ideas on which it was developed.

LOUIS DE BROGLIE

Heisenberg was born in 1901. At the time he was graduating from secondary school his native Germany was at war with most of the world: with Russia, the native land of Mendeleev; with England where Rutherford was making important discoveries in physics. It was also at war with France where, in 1892, Louis

Victor Pierre Raymond, Prince de Broglie, a descendant of kings and the future Nobel Prize winner, was born. De Broglie had not yet devoted himself to physics; he was enlisted in the army and was at the front. When the war ended, he began working in the laboratory of his elder brother Maurice, Duc de Broglie (1875-1960). His brother was studying the X-ray spectra of elements, and therefore Bohr's work was well known in his laboratory.

As many other scientists of that time, Louis de Broglie was also preoccupied with the same questions: "Why are atoms stable? And why doesn't the electron radiate when it is on a stationary orbit?"

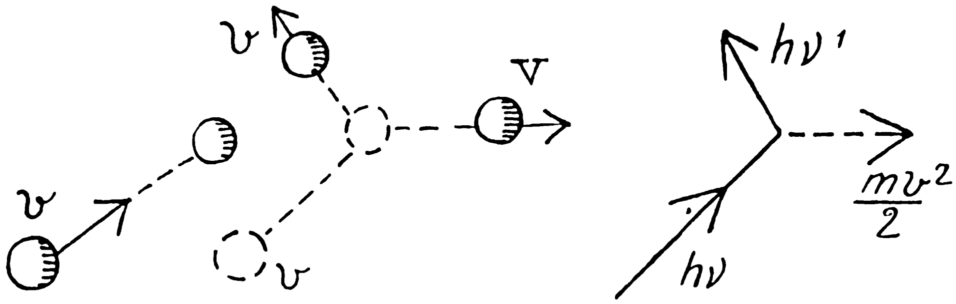
Bohr's first postulate distinguished these orbits from all the conceivable ones by the quantum condition that relates the radius r of the orbit, and the velocity v and mass m of the electron with a whole number of quanta of action h. Thus

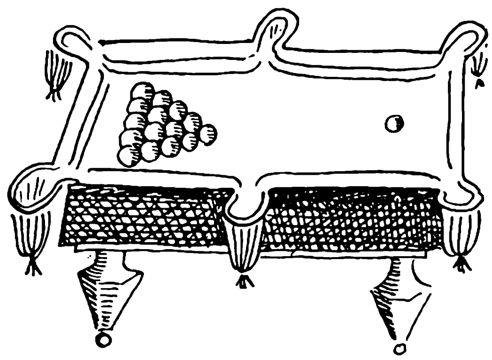
$$mvr = n\frac{h}{2\pi}$$

De Broglie wanted to find a reasonable basis for this condition, i.e. his aim was to explain it in terms of other, more usual concepts. (Or, as it is customary now to say, he tried to understand its physical meaning.)

Usually in seeking the explanation for incomprehensible facts, one resorts to analogies. This is exactly what de Broglie did in his search for a way out of the dead-end of contradictory concepts of the atom. He guessed that these difficulties are related to the ones that arose in attempts to understand the contradictory properties of light.

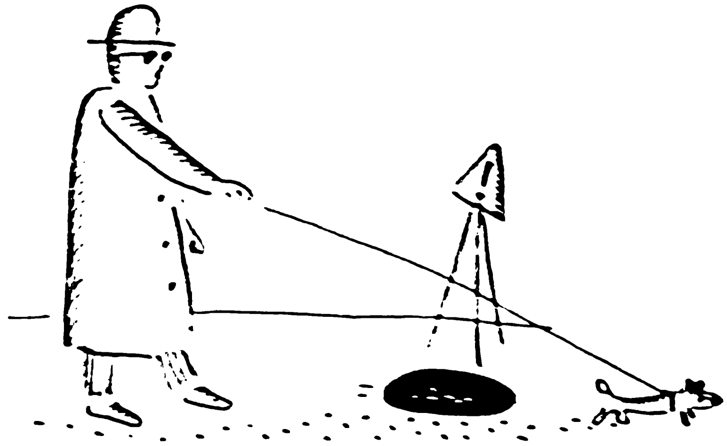
With respect to light, affairs became definitely muddled in 1923 when Arthur Compton conducted his famous experiment and showed that the scatter





of X rays by electrons in no way resembles the scatter of sea waves but, instead, is exactly like the collision of two billiard balls, one being the electron of mass m and the other a light quantum with the energy $E = h\nu$. After Compton's experiment, there could be no more doubt concerning the real existence of light quanta in nature, and that their energy $E = h\nu$ is uniquely related to the wavelength $\lambda = \frac{c}{\nu}$ to which these quanta correspond. In 1926, the American chemist Gilbert Newton Lewis proposed that they be called *photons*.

Neither de Broglie nor his contemporaries could explain the meaning of the words "Light quanta correspond to a light wave". They had no grounds, however, to cast doubt on experiments which indisputably demonstrated that under certain conditions a light ray behaves as a wave with length λ and frequency $\nu = \frac{c}{\lambda}$, and under others, as a flux of particles—



photons—with the energy $E=h\nu$ and momentum $p=\frac{h\nu}{c}$.

Three or four years later, physicists understood that this phenomenon was merely a special case of universal *wave-corpuscle duality* in nature, but at that time de Broglie had to feel his way along through entirely unknown country.

MATTER WAVES

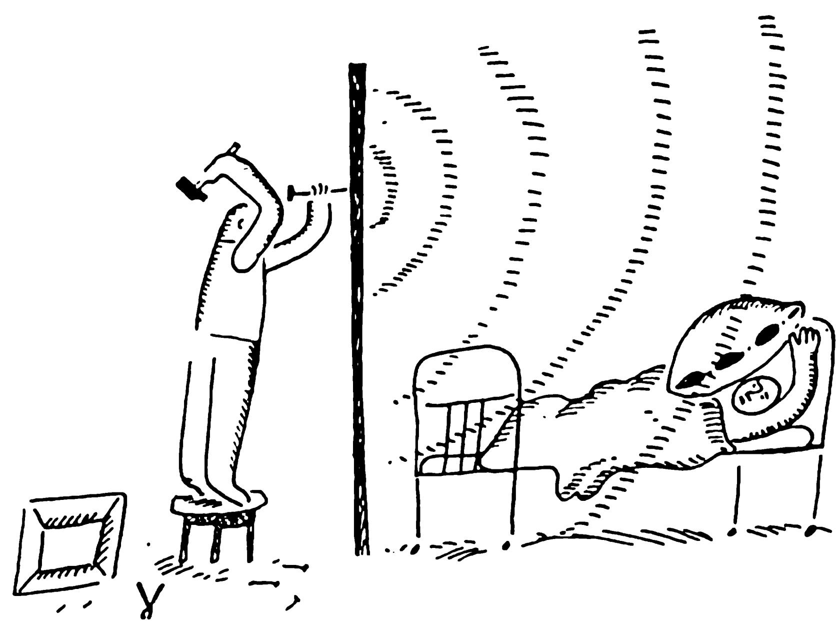
De Broglie believed in the unity of nature. He believed sincerely and deeply as had all great scientists before him. Therefore, he could not assume that a ray of light was something exceptional, unlike anything else in nature. De Broglie supposed that not only a light ray, but ***all bodies in nature must possess both wave and corpuscular (particle) properties simultaneously***. Therefore, besides ***light waves and particles of matter, quanta of light and waves of matter*** must also really exist in nature.

It is not easy to make such a simple and forcible statement; this requires courage and self-confidence. It is even more difficult to understand it; this requires an unbiased mind accustomed to abstract thinking. It is also extremely hard to conceive. Nature, accessible

to the perception of our five senses, has not created visualizable images capable of aiding us in these attempts. Indeed, when you hear the word "particle" anything could come into your mind—a grain of sand, a billiard ball, or a flying stone—but you would never think of sea waves or the vibration of a string. These are such contradictory images that it would seem unnatural to a normal person to unite them into one.

Any account of the birth of a new physical theory is inaccurate, even when given by its founder. Such an account almost inevitably employs concepts *that did not exist when the theory was being founded.* The concept of "matter waves" brings up a complex image in the minds of all present-day physicists that cannot be associated with anything we are accustomed to in the world around us. This image takes shape gradually in working with the formulas of quantum mechanics, and in solving atomic problems. It is difficult to describe in words. Naturally, de Broglie could not make use of such a complicated and highly perfected image in 1922. Hence in publications of those times we may find a certain substitute: the image of waves that are produced upon the vibration of a string.

It is well known that when we strike a taut string we produce a sound that depends upon the length of the string. The mechanism by means of which the sound is made is also well known: the vibration of the string is transmitted to the air, and we perceive the vibration of the molecules of air, and not that of the string that produced it. There is, however, a rigorous relationship between them. For instance, if we hear the note "la" from the first octave then, at that moment, the string is vibrating with a frequency $\nu = 440$ Hz (hertzes), i.e. 440 vibrations per second.



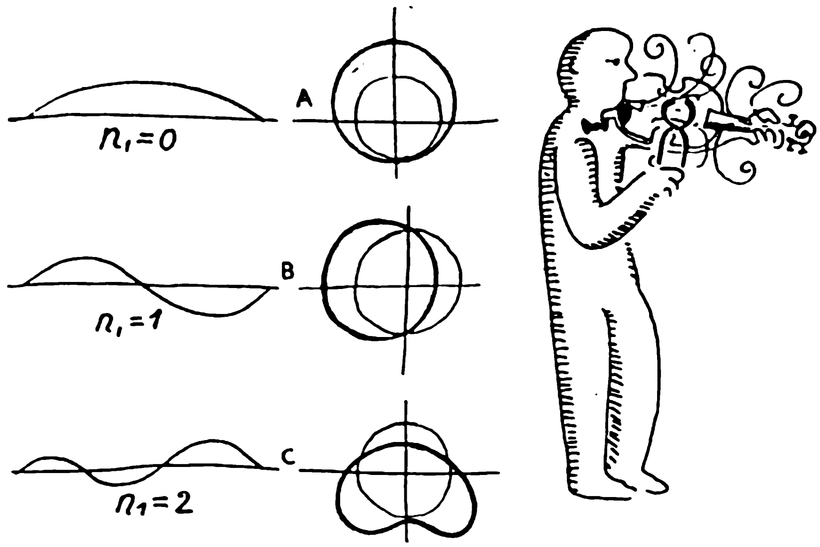
Since the velocity of sound in air is $v=334$ m/s, the length of the sound waves is

$$\lambda = \frac{v}{\nu} = 76 \text{ cm}$$

In the vibration of a string we hear the fundamental tone, the one due to the vibration of the string as a whole. However, additional vibrations, called overtones, are also produced. This complicates the picture of the vibration and "nodes" appear in the string. These are points that remain stationary in the process of vibration. However complex the vibration, one condition is always complied with: the length of the string accommodates a whole number of half wavelengths $\frac{\lambda}{2}$. For the fundamental tone the length of the string is exactly equal to half a wavelength $\frac{\lambda}{2}$. For the first overtone, it is equal to two half wavelengths, between which a stationary "node" is located, and so forth.

All of this de Broglie remembered when imaging the vibrating string. The rest was relatively simple.

Now we coil our strings into rings and picture them as orbits of the electrons in an atom. Then we repla-



ce the motion of the electron on these orbits by vibrations of waves that "correspond to the electron". De Broglie was sure that this was quite reasonable. It is evident that an additional node is formed in the string when it is coiled into a ring. This means that the fundamental tone of the taut string becomes the first overtone of the annular string. And this, in turn, means that at least one whole wavelength λ will be accommodated on the annular string, and not a half wavelength $\frac{\lambda}{2}$ (as previously on the plane string). Thus, the motion of the electron will be stable when, and only when, the length of the orbit accommodates a whole number n of "electron waves" λ. This leads to the simple condition

$$2\pi r = n\lambda$$

De Broglie compared this condition with Bohr's first postulate

$$mvr = n\frac{h}{2\pi}$$

and obtained the "wavelength of the electron"

$$\lambda = \frac{h}{mv}$$

That is all. It really is simple. But it is as simple as Planck's formula $E = h\nu$, Bohr's postulates, or Newton's law of universal gravitation, i.e. it is the simplicity of genius. Discoveries like these are simple because they require only the simplest of concepts. But in the development of man's intellect there have been only a limited number of such breakthroughs for they alter the very foundations of our thinking. You can never fully understand *how* they were accomplished. These are always miracles that even their founders are incapable of explaining. They can only strictly and simply repeat Newton's famous words, "I've known it for years".

De Broglie was 30 when he found his formula. But he had begun his search for it eleven years before, ever since his brother Maurice had returned from Brussels where he had been the secretary of the First International Solway Congress on Physics, the same congress of 1911 at which Planck had reported on the development of the "quantum hypothesis". The significance of the discovery and the vivid impressions of the elder brother concerning his contacts with the greatest physicists of that time so astounded the imagination of the younger brother that he could not forget them even during the war. Years of concentrated thought on this question were rewarded finally in 1922 by the hypothesis of matter waves. Now de Broglie could give a new definition of the concept of a "stationary orbit": *it is an orbit whose length accommodates a whole number of "electron waves"* λ.

If this is really so, then the problem of the stability of the atom does not exist since in the stationary state the electron is like a string vibrating in a vacuum without friction. Such vibrations are not damped and therefore the electron can remain in a stationary state forever if there is no external influence.

It is hardest of all to declare a new hypothesis. This is always an illogical process. But as soon as it has been stated, rigorous laws of logic enable all the consequences to be derived. The main one is obvious: if "matter waves" exist they can be observed and measured. They actually were discovered and their reality was proved with the degree of certainty that is at all attainable in physics. But this happened four years later and we shall deal with it in its proper place.

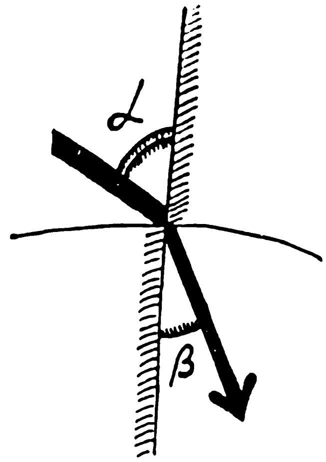
De Broglie wrote down his formulas in 1923, two years before the works of Heisenberg and Schrödinger were published. The simplicity of the formulas and the lucidity of the main idea reminded one of Bohr's postulates. In exactly the same way as Bohr's postulates, de Broglie's ideas had not yet become atomic theory. For this it was necessary to write them in the language of equations. When Werner Heisenberg founded matrix mathematics, he thereby converted Bohr's ideas into precise formulas and rigorous equations.

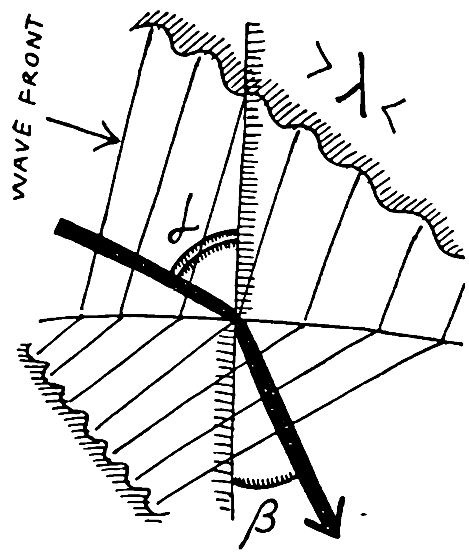
De Broglie's ideas became the basis for the wave mechanics that was founded by Erwin Schrödinger.

OPTICAL-MECHANICAL ANALOGY

Now we must discuss several new facts. They may not at first seem very simple, but it is essential to understand them, unless we wish endlessly to repeat the slick, rounded phrases about the "mysterious country of the microcosm" which only clutter up the mind since they turn out to have no significance on close examination.

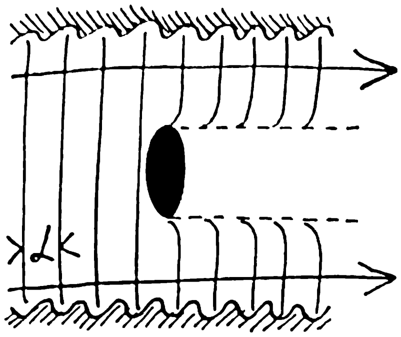
Whether we speak of atoms or of quanta, we return, time and again, to the properties of a ray of light. This is no coincidence. Essentially, these properties embody all of present-day physics. We shall again,

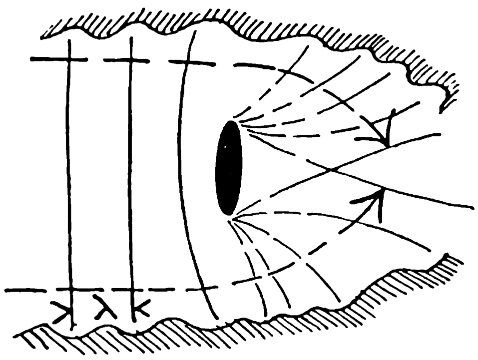


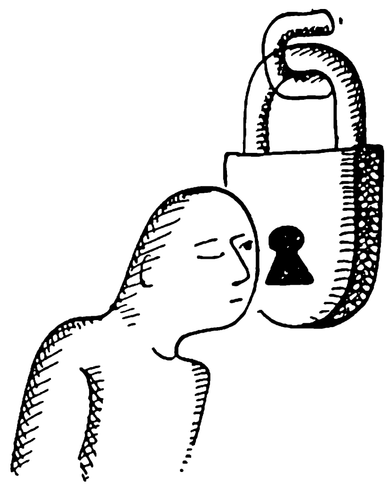


more intently now, examine them. Hence, we shall return to Sir Isaac Newton and recall the gist of his argument with Christiaan Huygens on the nature of the light ray.

It is common knowledge that in a void a beam of light propagates in a straight line. This knowledge is one that a person acquires in childhood without resorting to science or any physical instruments, simply by bumping his head several times against the corner of a table. Subsequently, this knowledge enables him to avoid many other hazards, and gradually he becomes convinced of its truth. Physics textbooks usually have illustrations demonstrating the propagation of a light ray, in which a straight line is drawn between the light source and the eye of the observer. This shows the imaginary *trajectory of the light beam.*







Both in its meaning and in the images rising from it, the trajectory of a light beam in no way differs from the trajectory of motion of a particle. This is why in Newton's time light was thought to be a flux of very small particles (corpuscles). Of course, the path of these "particles of light" (as that of ordinary particles) could be bent when passing, for instance, from the air into water, but the concept of a trajectory can be retained here as well. In everyday life this concept is useful and leads to no misunderstandings. It helps us to avoid ill-fated encounters with automobiles in the streets, to determine the positions of the stars in the sky, and to design photo cameras.

With the development of experimental physics, mankind extended the narrow limits of everyday experience and discovered new properties of the light ray. It was found to lose its customary properties entirely if it passes around a "very small obstacle". Physics is a quantitative science, and such indefinite statements have no significance for it. Small, but in comparison with what?

Christiaan Huygens conceived of the propagation of light as the vibrations of a certain "luminiferous ether" ("light-carrying ether"). The image formed by this conception in our mind resembles the circles originated when we throw a stone into a pond or endless rows of sea waves. Physicists ceased to doubt the legitimacy of these images after the works of Maxwell and Hertz who conclusively proved that light is simply a special case of electromagnetic oscillations.

Let us recall what was mentioned in the first chapter about the principal characteristic of all wave processes being their frequency or wavelength. Now this statement acquires a definite meaning: "A ray of light loses its customary properties if the size of the obstacle is commensurate with the wavelength." In this case the light ray no longer propagates in a straight line; the phenomenon of diffraction occurs. Moreover, certain of the waves of the ray begin to interact. They reinforce and cancel one another or, as physicists say, they begin to interfere. Both phenomena, *diffraction* and *interference*, produce a diffraction pattern on a screen that is quite difficult to understand from Newton's point of view. The wave theory of light has no trouble explaining this pattern; this was the decisive factor in the victory of the Huygensian waves over the Newtonian particles.

As time went on physicists became so accustomed to the properties of light that they became a sort of standard for all wave processes in general. Now, if in any process whatsoever the phenomena of interference and diffraction were observed, no one doubted that it was of a wave nature. This, in fact, was the reason why de Broglie's hypothesis on matter waves was recognized immediately by physicists as soon as they saw the first photographs of electron diffraction.

Look at the three very similar photographs on page

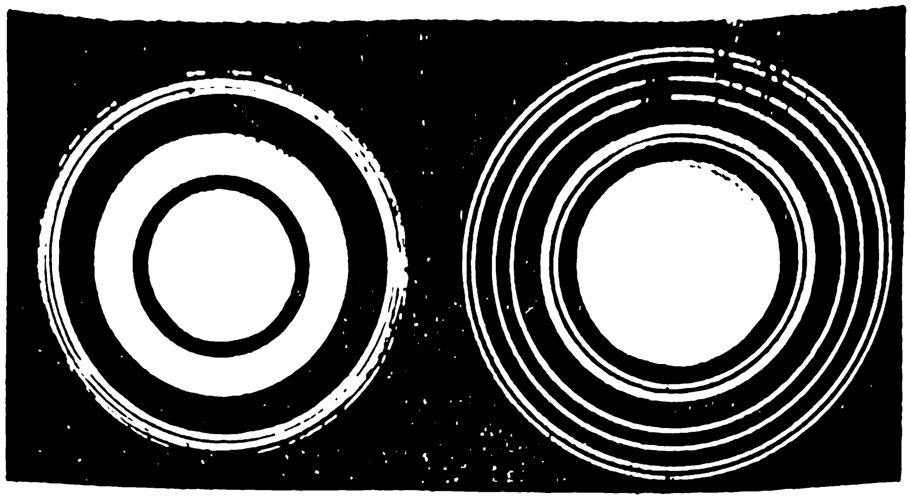
212: the one at the left shows the diffraction of visible light; that at the right, the diffraction of electrons, and the one below shows waves of water. Looking at them, it is quite difficult not to believe in the wave nature of the electron. This is no longer a question of belief for the present generation of physicists, but a fact of precise knowledge and even a means for technical applications.

One discrepancy remained in the orderly theory of wave optics: we perceive a beam of light as a beam, and not as a wave. How can this fact be explained from the viewpoint of wave optics? This problem was solved by Augustin Jean Fresnel and an explanation can be found in any textbook of physics.

It turned out that in interference all the waves from a source of light cancel one another except those that are within a narrow channel one half wavelength thick. (For visible light the thickness of the channel is $\frac{\lambda}{2} \approx 3 \times 10^{-5}$ cm.) If we neglect the thickness of the "light channel" we shall obtain the trajectory of the light beam that we all know so well in ordinary life.

The method of constructing this trajectory is also known. First you must draw a line through all the wave crests or, as they say in physics, mark the *wave front*. Then a line is drawn from the light source perpendicular to the wave front. This will be the *trajectory of the light ray*. If the wave front is distorted near an obstacle, the trajectory will simultaneously be bent. Thus the ray of light will bend around the edge of the obstacle and diffraction will occur.

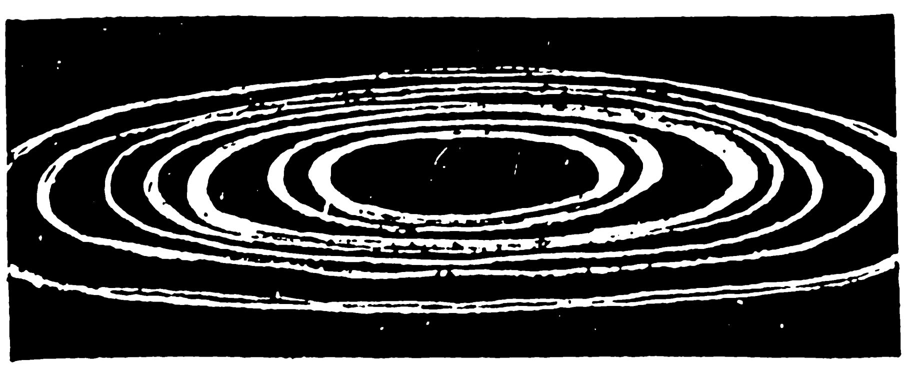
In 1834, William Rowan Hamilton (1805-1865), the famous professor of astronomy at the Dublin University, was working on a problem that was incomprehensible to his contemporaries. He was trying to prove that the formal analogy between the trajectory of mo-



tion of a particle and the trajectory of a light ray had a rigorous mathematical meaning.

We already know that in physics the concept *laws of motion* corresponds to formulas, the *equations of motion*. They are entirely different for waves and particles. In one case we solve the formulas to find the *trajectory of the particle*; in the other, to find the shape and velocity of the *wave front*. But we also know that in geometrical optics we can draw the trajectory of the light ray if we know the motion of its wave front.

Hamilton proved that in mechanics we can do something that is the exact opposite. We can replace the trajectory of a particle by the motion of the front of a certain wave. Or, more precisely, we can write equations of motion in mechanics in a form in which they fully coincide with the equations of geometrical



optics which describe the propagation of a light ray without taking its wave properties into account. Hamilton proved the validity of the *optical-mechanical* analogy, i.e. that the motion of a particle along a trajectory can be represented as the propagation of a light ray when its wave properties are not taken into consideration.

SCHRÖDINGER'S WAVE MECHANICS

In 1911, Erwin Schrödinger (1887-1961) graduated from the Vienna University which was still steeped in the traditions of Christian Johann Doppler, Armand Hippolyte Fizeau, Ludwig Eduard Boltzmann and the whole spirit of the classical age in physics: soundness in studying phenomena and the display of a leisurely interest in them. By 1925, he was a professor of the Zurich University, no longer young, but still retaining the youthful urge to understand the most vital problem posed by the physicists of his day: "What is the structure of the atom, and how do the electrons travel in it?"

At the end of 1925, Schrödinger read in one of Einstein's articles several words of praise concerning de Broglie and his hypothesis. This sparse information proved to be sufficient for him to believe in the matter wave hypothesis and to develop it to its logical conclusion (which is always difficult, and not only in science).

The course of his reasoning is easy to understand, at any rate now, almost half a century later. First of all, he recalled Hamilton's optical-mechanical analogy. He knew that it had been proved only within the limits of geometrical optics, when the wave properties of light can be neglected. Schrödinger went

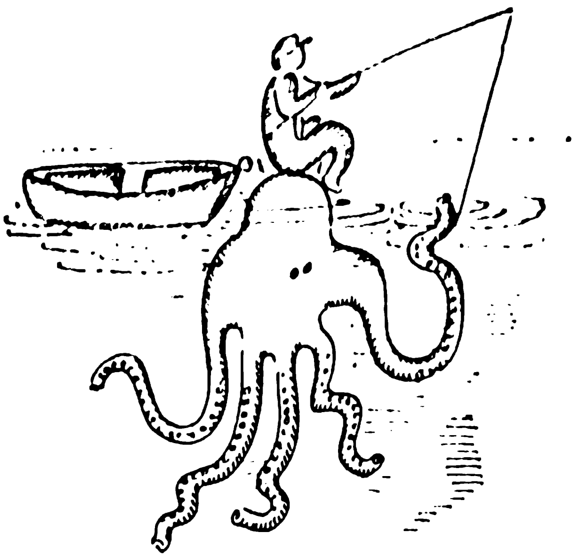
further and assumed that the optical-mechanical analogy remains valid even for wave optics. This means that *any motion of a particle is always similar to the phenomenon of wave propagation.*

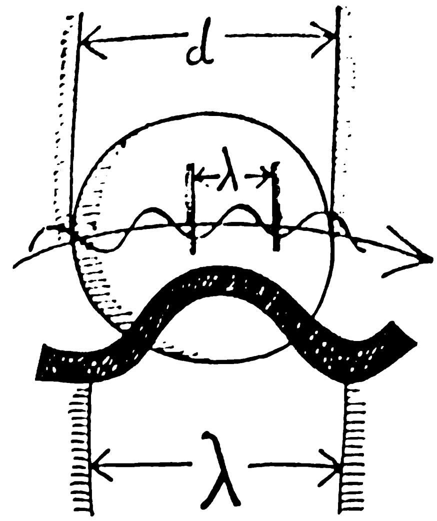
As with any fundamental discovery, Schrödinger's hypothesis did not follow logically from anywhere.

But, like any discovery, it did have logical consequences.

First of all, if Schrödinger's idea was correct, then the motion of the particles should display wave properties in regions of space whose dimensions are commensurate with the wavelength of these particles. To a great extent this also concerns the motion of an electron in an atom. Comparing the formulas of de Broglie $(\lambda=\frac{h}{mv})$ and Bohr $(mvr=\frac{h}{2\pi})$, it is evident that the atom's diameter $d=\frac{\lambda}{\pi}$ is approximately one-third of the electron's wavelength λ. But this length is the only one mentioned when we speak of the size of the electron in the atom. Now it becomes obvious that it is impossible to conceive of it as being a particle in the atom as otherwise we will have to assume that the atom is made up of particles larger than itself. This leads at once, and somewhat unexpectedly, to Heisenberg's postulate: *no concept exists of the trajectory of an electron in an atom.*

As a matter of fact, something larger cannot travel inside something smaller and, what is more, along some kind of trajectory. But then there is no problem of the stability of the atom since electrodynamics only forbids the electron to travel in the atom along a trajectory; it is not responsible for phenomena that occur in other kinds of motion. All this means that electrons exist in the atom not as particles but as certain waves the significance of which we shall understand somewhat later. What is clear now is that what-



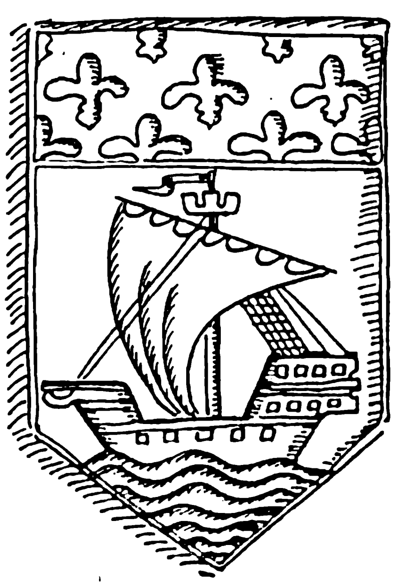


ever the nature of these electron waves, their motion must obey a *wave equation.* Schrödinger derived this equation. Thus

$$\frac{d^2\Psi}{dx^2}+\frac{2m}{\hbar^2}\left[E-U(x)\right]\Psi=0$$

This is absolutely incomprehensible to those who see it for the first time and can induce only curiosity or a feeling of instinctive objection, without serious grounds for the latter.

Indeed, the following drawing is just as baffling as Schrödinger's equation but we accept it without



any inherent resistance. We shall calm down entirely when we find out that this is simply the coat of arms of the city of Paris that we may never have visited nor ever will. Only the most finicky readers may try to find out why it looks the way it does and not otherwise. As in Schrödinger's equation, each line and symbol in this coat of arms is full of meaning. At the top are fleurs-de-lis, irises or lilies, that first appeared as a heraldic emblem of the French royal family and France by the end of the fifth century, after the victory of Clovis I over the Huns on the banks of the River Lys (according to legend, the soldiers of Clovis, when they returned home, decorated their helmets and shields with white lilies). The ship in the lower field is of an outline resembling the Ile de la Cité, the island in the Seine River which was the home of the ancient Gallic tribe called the Parisii from which the city of Paris got its name. The shape of the coat of arms resembles a sail in memory of the main occupation of the ancient inhabitants of Paris. As one can see, it is not difficult to decipher the coat of arms, although it is really dear only to Parisians.

Let us deal with Schrödinger's equation in exactly the same way. We shall accept it at first as a symbol of quantum mechanics, as a coat of arms of the quantum country through which we are travelling, and make an attempt to understand why it is as it is. Certain features of this coat of arms are already familiar: m is the mass of the electron, $\hbar$ is Planck's constant h divided by 2π, E is the total energy of the electron in the atom, $U(x)$ is its potential energy, and x is the distance from the nucleus to the electron. It may be somewhat more difficult to understand the symbol of the second derivative $\frac{d^2}{dx^2}$ but this cannot be helped for the time being. At first we will just have to remem-

ber that this is a symbol of differential calculus and, consequently, Schrödinger's equation is thereby a differential equation.

The most complicated matter is to understand what the Ψ-function (read as *psi-function*) represents. This is really difficult and even Schrödinger misinterpreted its meaning in the beginning. We shall deal with it somewhat later. For the present, it is important to understand the following: notwithstanding its singularity, the psi-function does somehow represent the motion of the electron in the atom. Not in the same way as Heisenberg's matrices $\{X_{nk}\}$ and $\{P_{nk}\}$, but still it does, and quite well. So well that with its aid many problems of quantum mechanics can be solved simpler and more rapidly than with Heisenberg's matrices.

Physicists soon appraised the advantages of wave mechanics, of its generality, elegance and simplicity. Since then they have almost abandoned matrix mechanics.

But this was not an easy victory.

ROUND AND ABOUT THE QUANTUM

COMPTON'S EXPERIMENT

Imagine that you are standing before a mirror dressed in a green sweater and suddenly see yourself dressed in a red sweater. First of all, you rub your eyes and, if that doesn't help, you go to an oculist. Because what you see is simply impossible. Indeed, green rays are waves with a length $\lambda = 5500$ Å. When, along their path, they meet an obstacle, the mirror, they are reflected but can by no means change their wavelength and become, for instance, red ($\lambda = 7500$ Å). But this phenomenon is exactly what Compton observed. Allowing a beam of X rays with a wavelength λ to strike

a target, he found that the wavelength λ' of the scattered waves is longer than those of the incident ones. The scattered rays are thus really "redder" than the initial rays!

This marvel can be understood if we recall Einstein's hypothesis about the quanta of light that he proposed to explain the photoelectric effect. Indeed, in place of X rays with a wavelength λ and frequency $\nu = \frac{c}{\lambda}$, we must picture a flux of particles, quanta with the energy $E = h\nu$. Colliding with the electrons of the atoms in the target, the quanta eject them (expending the energy P), accelerate them to the velocity v (additionally expending the energy $\frac{mv^2}{2}$) and are themselves scattered with lesser energy $E' = h\nu'$. Evidently

$$h\nu = h\nu' + P + \frac{mv^2}{2}$$

If the atom completely absorbs the light quantum ($E' = 0$), we observe the ordinary photoelectric effect and Compton's equation is converted into Einstein's equation

$$h\nu = P + \frac{mv^2}{2}$$

Both these experiments can be done in a Wilson cloud chamber, observing the path of each ejected electron and thereby visualizing the collision of a light quantum with an electron.

But this being so, what is there to prevent us from seeing ourselves in a red sweater in the mirror? Again it is the quantum laws which forbid an electron to absorb arbitrary portions of energy. In a stationary orbit in the atom an electron can absorb only a quantum that can transfer it from one stationary state to another, or eject it from the atom (remember Franck and Hertz's experiment). The energy of the "green

quanta" (of a wavelength $\lambda = 5.5 \times 10^{-5}$ cm $= 5500$ Å) equals

$$E = h\nu = \frac{hc}{\lambda} = \frac{6.62 \times 10^{-27} \times 3 \times 10^{10}}{5.5 \times 10^{-5}} = 3.6 \times$$
$$\times 10^{-12} \text{ erg} \approx 2 \text{ eV (electron volts)}$$

This is much too small an amount to eject the electron from the atom (five times as much is required: $P \approx 10$ eV). Therefore, the quanta elastically bounce off the atoms of the mirror (with no loss of energy) and, consequently, become no redder.

X rays, with their extremely short wavelength ($\lambda \approx 1$ Å), present an entirely different picture. Their energy is about 5 to 10 thousand times higher, and therefore the phenomena that occur are quite different. For example, they are not reflected at all by the mirror but pass through it, stripping electrons from its atoms on their way.

As a matter of fact, even the simple process of reflecting green light from a mirror is somewhat more complicated than we have presented it here. But there is another difficulty, and a vital one. In our orderly picture, where instead of waves of light we have only quanta of light, there is no room for the experiments of Friedrich, Knipping and Laue, who discovered the diffraction of X rays and thereby demonstrated their wave nature.

How can we reconcile these incompatible conceptions of ray-waves and ray-quanta?

In the following chapter we shall see that quantum mechanics was able to cope with this task.

THE ELECTRON: PARTICLE OR WAVE?

This is not a matter we ponder over every day, just as we rarely bother about how a telephone is made. We simply employ various apparatus in which the

electron is "at work", such as a TV set, an X-ray unit, or an electron microscope. But if we just think for a minute about the design of these devices, the question of the nature of the electron loses its academic aspect at once.

The image is obtained in the picture tube of a TV set by means of electrons that are accelerated by a voltage of approximately 10,000 V. This imparts to them a velocity of $v \approx 5 \times 10^9$ cm/s, which is already one-sixth of the velocity of light. Their wavelength can easily be computed by de Broglie's formula $\lambda = \frac{h}{mv}$; it is equal to $\lambda \approx 0.1$ Å, i.e. only one-tenth of the size of the atom. Since electrons propagate in a straight line in a TV set, we perceive them as a flux of particles.

The same electron behaves as a wave in an electron microscope. A beam of electrons is accelerated by a voltage of 100,000 V to a velocity of 10^{10} cm/s which corresponds to a wavelength of 0.05 Å. Besides, the beam passes through a system of magnetic lenses exactly as in an ordinary microscope the beam of light passes through optical lenses. It is well known in wave optics that, owing to the phenomenon of diffraction, you cannot see an object even in the best microscope if its size is less than one half of the wavelength of the light that illuminates it. The wavelength of visible light is 5000 Å. Hence, in an optical microscope one can distinguish objects of a size exceeding 2500 Å. The size of bacteria is greater than 10^{-4} cm $=$10,000 Å and they are therefore readily observed in an ordinary microscope. But viruses are invisible in such microscopes; they are of a size less than 1000 Å (the diameter of the influenza virus is only 800 Å).

Theoretically an electron microscope enables you to distinguish objects as small as 0.02 Å, i.e. only

one-fiftieth the size of an atom. Does this mean that we can examine a separate atom in this way? No, of course not. The binding energy (P) of the electron in the atom is equal to about 10 electron volts (the energy acquired by an electron in passing through a potential difference of 10 V). In an electron microscope the electrons acquire an energy of about 100 thousand electron volts. Such "rays" destroy any atoms they collide with. (Just imagine trying to obtain the shadow of a dust speck on a wall by shooting shotgun shells at it!) Actually, objects as small as 5 or 10 Å, i.e. 5 or 10 times larger than an atom, have been distinguished in electron microscopes.

ELECTRON DIFFRACTION

As many other discoveries in physics, electron diffraction was first observed "by chance" although, as Louis Pasteur liked to repeat, "chance speaks only to the mind made ready to hear".

In 1922, the Bell Telephone Laboratories engaged Clinton Joseph Davisson (1881-1958) to do certain research. Davisson and his assistant were studying the reflection of electron beams from the surface of metals and suddenly noted certain anomalies. In 1925, after de Broglie had published his work on matter waves, Walter Maurice Elsasser, a student of Max Born, suggested that these anomalies were due to electron waves. Davisson read this article but attached no especial importance to this idea. But in 1926, when he came to Europe and showed his plots to Max Born and James Franck in Göttingen and to Douglas Rayner Hartree at Oxford, they unanimously recognized them as being de Broglie waves. On his return voyage across the Atlantic, Davisson studied Schrödinger's work and, soon after his arrival, together with

Lester Halbert Germer (born 1896), confirmed de Broglie's hypothesis by an experiment.

Sir George Paget Thomson (born 1892) approached the problem from the other end. From the very start he regarded de Broglie's hypothesis with great sympathy and, soon after Davisson's visit to England, began to devise some experimental method of proving it. After the work that had been done by Crookes and J. J. Thomson, experiments with cathode rays had become a customary element in education. It is perhaps for this reason that G. P. Thomson started by thinking how he could adapt them for his new experiments. Almost at once he found suitable equipment in Aberdeen, in use at the time for research carried out by the student Alexander Reid (who was killed soon after in an automobile accident at the age of 22). In only two months time they had obtained excellent photographs of electron diffraction on this apparatus. It exactly resembled X-ray diffraction. This was to be expected since in their experiments the electrons were accelerated by a potential of 150 V (the usual voltage of the city mains). The wavelength of such electrons is about 1 Å $=10^{-8}$ cm. This is commensurate with the wavelength of X rays and the size of atoms.

An interesting item is the fact that George Paget Thomson is the son of the famous J. J., Sir Joseph John Thomson, who established, at the turn of the century, that the electron is a particle. By the irony of fate, thirty years later, his son proved that electrons are waves. Both are right, and both have been awarded Nobel Prizes for their discoveries.

Chapter Eight

WAVE-CORPUSCLE DUALITY * HEISENBERG'S UNCERTAINTY RELATION * COMPLEMENTARITY PRINCIPLE

At the beginning of the twenties, the physicists Max Born and James Franck and the mathematician David Hilbert organized a "seminar on matter" in Göttingen. (It was here that the term "quantum mechanics" was first employed as far back as 1924, long before the works of Heisenberg and Schrödinger were published.) It was attended by renowned scientists of that time as well as by young physicists who were later to become famous. Hilbert began almost each seminar with the question: "So, gentlemen, like you, I wish somebody would tell me—exactly what is an atom?"

Today we know more about the atom than all the participants of the seminar did at that time, but we are still not ready to answer Hilbert's question. The point is that we have discovered a great many *facts* but we lack *conceptions* that can correctly explain these facts.

Thanks to Niels Bohr, even now, after so many years have passed, we involuntarily picture a tiny planetary system with a nucleus and electrons when we hear the word "atom". We must exert our will-power to

remind ourselves that it also has wave properties. Now, as before, both ideas, the "electron wave" and the "electron particle", exist independently in our consciousness and unwittingly we try to get rid of one of them. "Electron or wave?" Physicists returned time and again to the question in the twenties, striving for definiteness as all people do.

A peculiar situation had arisen in atomic physics by the beginning of 1926. Two systems of quantum mechanics had been evolved simultaneously, separately and independently, whose premises widely differed. Heisenberg, following Bohr, was sure that the electron was a particle, and derived his matrix equations with this conviction. Schrödinger, on the other hand, could derive his differential equation, believing, together with de Broglie, in the wave properties of the electron.

Heisenberg demanded that the equation contain only quantities that can be directly measured in an experiment, such as the frequency of spectral lines and their intensity. On this basis he excluded from the theory the concept of the "trajectory of the electron in the atom" as a quantity which, in principle, is unobservable. Schrödinger also had no use for the concept of a trajectory, but wrote down his equation for the psi function which also cannot be measured and whose meaning was still unclear to him.

Experiment, the final judge in all controversies, was at first decidedly on the side of matrix mechanics. Faraday's experiments showed the indivisibility of the electric charge, and this was strictly proved by the subsequent experiments of Crookes and Thomson. Only a particle could possess this property. Millikan's experiments and the photographs of traces of electrons in a Wilson cloud chamber dispelled the last doubts that anyone might still have had.

The concept of an electron as a particle, however, sharply contradicted the fact of the astounding stability of the atom. Time and again have we emphasized that the planetary atom is unstable. Bohr devised his postulates precisely in order to explain the stability of the atom and, at the same time, to save the concept of the particle electron.

De Broglie and Schrödinger went a different way and showed that the stability of the atom could be most naturally explained if one assumed that the electron was a wave and not a particle. This hypothesis was soon confirmed by the direct experiments of Davisson, Germer and G. P. Thomson who discovered that the electron is capable of diffraction.

It is customary to believe experiments. But how can you believe two experiments if they exclude each other? The situation that developed had had precedents in the history of physics. Nevertheless, it was so unusual that nobody suspected at first that the two systems of mechanics comprised a single entity and hence most physicists were trying to prove the validity of one and the falsity of the other. There were bitter arguments between the advocates of the two theories. Some upheld the rights of the first-born matrix mechanics; others preferred the mathematical simplicity of wave mechanics. Schrödinger put an end to these debates at the beginning of 1927 when he proved that both systems of mechanics are *mathematically equivalent*. To each physicist this meant that they were also equivalent *physically*, and that he was dealing with one and the same mechanics—the *mechanics of the atom*—but written in different forms. This also signified that the initial premises of the two systems—the concept of the electron as a particle in matrix mechanics and as a wave in wave mechanics—were also true.

The more scientists found out about the atom, the less downright were the questions they put to nature. In the times of Planck and Einstein, physicists wanted to know: "What is a ray of light, a wave or a flux of particle-quanta?" After the work of de Broglie they went on trying to clear up the question: "What is an electron, a wave or a particle?" Gradually, and with great difficulty, did the simple idea crop up: "Why should it be *or*? Why must these properties, those of a wave and of a particle, exclude each other?" A sober and sensible approach revealed that there are no logical grounds for the alternative "either ... or". The only reason for not abandoning it is the same old inertia of thinking; we always attempt to interpret new facts by means of old concepts and images.

There exists still another difficulty, a psychological one. In our everyday life we have become accustomed to the fact that the smaller an article, the simpler it should be. For example, of the 33 matreshkas (wooden dolls painted as Russian peasant women with successively smaller ones fitted inside) the innermost 33rd matreshka is the simplest. A billiard ball is considerably simpler than the terrestrial globe, and the whole always consists of simpler parts. When, sitting by the seashore, Democritus divided his apple, he may have imagined the atom in any way whatsoever, but hardly as being more complex in structure than the whole apple. It really isn't, of course. But sometimes certain properties are evident for small articles and unnoticeable for large ones. In exactly the same way, when we divide up matter (which, by tradition, we imagine to be made up of particles) its new wave properties do not appear; they are *manifested*. It al-

ways possessed these properties; we simply did not notice them before.

We encounter phenomena of this kind much more often than we realize. A billiard ball and the terrestrial globe are both spheres and, in this, they resemble each other. But how many people had suffered for this truth before the earth became a sphere for everybody. The curvature of a billiard ball, on the other hand, was always obvious, even to the perpetrators of the Spanish inquisition. The whole matter lies in the proportions of the phenomenon and its observer. The earth, in precisely the same way as each of its electrons, has wave properties. If, however, we try to describe its motion by means of Schrödinger's equation then, its mass being 5×10^{27} grams and the velocity with which it travels around the sun being 3×10^{6} cm/s, we must ascribe this "particle" a de Broglie wavelength of 4×10^{-61} cm. This number is so small that we have no idea of how it is to be understood.

This cannot, however, be accepted as grounds for asserting that the earth does not have wave properties. We cannot measure the curvature of the earth by using dividers and a ruler but it is round nevertheless.

The number of such examples can be easily augmented, and each one will, in its way, help us to understand the final result of the meditation on the "wave-particle" question.

No "wave *or* particle" problem exists. An atomic object is both "a wave *and* a particle" *simultaneously*. Moreover, *all* bodies in nature possess wave and corpuscular properties simultaneously, and these properties are but different manifestations of a united *wave-corpuscle duality*.

This idea occurred to Bohr, Kramers and John Clarke Slater as far back as 1924. In a joint work they de-

finitely claimed that the wave nature of light propagation on one hand, and light absorption and the emission of quanta on the other, are the experimental facts that should be used as the basis for any atomic theory, and for which no explanations should be sought.

The uncustomary unity of the "wave-particle" properties is indicated in the formulas of both Planck ($E=h\nu$) and de Broglie ($\lambda=\frac{h}{mv}$). The energy E and mass m are characteristics of a particle; the frequency ν and wavelength λ are features of a wave process. The only reason we do not notice this duality in our everyday life is the smallness of Planck's constant

$$h=6.626189\times10^{-27}\ \mathrm{erg\cdot s}$$

Even if this is a chance circumstance, it must be taken into account.

If we lived in a world where Planck's constant was commensurate with customary scales, our impressions of this world would differ strongly from the ones we have now. For instance, it would be difficult for us to visualize houses with sharp, clear-cut outlines, or a locomotive standing entirely at rest. Furthermore, there could be no railway schedules whatsoever in this world, no tracks (trajectories) could be laid, and only the stations of departure and destinations of the trains could be indicated. Such a world is hypothetical, of course; we are quite unable to alter the value of Planck's constant at will. It is always unchanged and very small. But atoms are also so small that Planck's constant is commensurate with their scales. "For them" this unusual world really exists and we will now try to understand its uncommon logics in much the same way as Gulliver had to become accustomed to the morals and manners of the Lilliputians.

HEISENBERG'S UNCERTAINTY RELATION

Assume that we have become so inspired with the idea of the indivisibility of the "wave-particle" properties, that we wish to write down our accomplishment in the precise language of formulas. These *formulas* should establish the relationship between *numbers* which correspond to the *concepts* "wave" and "particle". In classical mechanics these concepts are strictly differentiated and refer to entirely different phenomena of nature. In quantum mechanics the wave-corpuscle duality compels us to employ both concepts simultaneously and to apply them to the same object. This necessary step is not gratis; we shall have to pay for it, and pay dearly.

This became entirely clear in 1927 when Werner Heisenberg guessed that though both concepts, "particle" and "wave", can be equally well applied to an atomic object, *they can be strictly defined only separately*.

In physics the words "to define a concept" mean "to indicate a method of measuring the quantities to which this concept corresponds".

Heisenberg contended that it is impossible to measure both the coordinate x and the momentum p of an atomic object simultaneously with perfect accuracy. This means, with due consideration for de Broglie's formula $\lambda = \frac{h}{p}$, that it is impossible to determine the position x of an atomic object and its wavelength λ simultaneously and with absolute precision. Consequently, the concepts "wave" and "particle" have a restricted meaning when used *simultaneously* in atomic physics. Furthermore, Heisenberg found the numerical value of this restriction. He showed that if we know the position x and momentum p of a particle

of atomic magnitude with the amounts of error δx and δp, we cannot improve the accuracy to reduce these errors to infinitely small values; we can do this only as long as the unequality, called the *uncertainty relation*, is complied with. Thus

$$\delta x \times \delta p \geqslant \frac{1}{2} h$$

This limit is very small, but it exists and this is a fundamental fact.

The uncertainty principle, also called the principle of indeterminacy, is a rigorous law of nature which is in no way related to the lack of perfection of our measuring instruments. It states that it is *impossible in principle* to determine both the coordinate and momentum of a particle simultaneously more accurately than is permitted by the above inequality.

It is *impossible* in exactly the same way as it is impossible to exceed the velocity of light or to reach the absolute zero temperature. It is as impossible as to lift oneself by one's hair or to return to yesterday. References to the omnipotence of science are out of place here. The power of science is in its capacity to discover, understand and make use of the laws of nature and not in violating them.

This may seem a little strange to us. We are used to the feeling that science is all-powerful and have eliminated the statement "it is impossible" from its vocabulary. It is notable, however, that the greatest triumph in any science is attained precisely at the moment such forbiddances are established with the participation of the word "impossible". When it was said: "It is impossible to build a perpetual motion engine", thermodynamics was evolved. As soon as it was found that it is "impossible to exceed the velocity of light", the theory of relativity was born.

Quantum mechanics acquired its final form only after it was understood that it was impossible to measure various properties of atomic objects simultaneously with arbitrary accuracy.

Upon first acquaintance with the uncertainty relation, we have an instinctive resentment toward it and say, "This cannot be!" Heisenberg explained the matter by discarding still another idealization of classical physics: the *concept of observation.* He proved that in atomic mechanics it must be revised just as the concept of motion was.

An overwhelming share of his knowledge of the world is acquired by a person by means of his sight. This feature of man's perception has been the determining factor in his whole system of cognition. Almost everyone, on hearing the word "observation" thinks of a person attentively looking at something. When you look at the person you are talking to, you are absolutely sure that even if you stare at him and even if your glare is one that chills the blood, you can do him no physical harm. This sureness is essentially the basis for the concept of observation in classical mechanics. Classical mechanics had sprung from astronomy and, since no one doubted that the stars were unaffected by our observing them, this principle was accepted without objections for all other kinds of observation.

The concepts of "phenomenon", "measurement" and "observation" are closely related to one another but by no means do they coincide. The ancients *observed* phenomena; this was their method of studying nature. From these observations they then derived consequences by means of pure speculation. From then on the conviction has evidently taken root that *phenomena exist independently of their observation.*

We have repeatedly emphasized the chief distin-

ction between modern physics and that of ancient times. Modern physics has substituted experiment for speculation. Present-day physics does not deny that phenomena exist in nature independently of their observation (and, of course, of our consciousness). But it also asserts that these phenomena become objects of observation only after we can indicate a precise method for measuring their properties. *In physics the concepts of "measurement" and "observation" are inseparable.*

Any measurement implies interaction between the instrument and the object being investigated. Any interaction, in its turn, disturbs the initial states of both the instrument and object. Thus, as a result of measurement, we obtain data that are distorted by the interference of the instrument. Classical physics assumed that all such distortions could be taken

into account, and that the "true" state of the object could be established from the results of measurements and independently of them. Heisenberg proved that such an assumption is a delusion and that *in atomic physics the "phenomenon" and its "observation" are inseparable from each other*. Essentially, an "observation" is also a phenomenon and far from being one of the simplest.

Like many other aspects of quantum mechanics, such an assertion is unusual and arouses our unconscious protest. We shall nevertheless try to understand it or, at least, to sense its meaning.

We can readily see in our everyday life that the smaller the object we are examining, the easier it is to disturb its state. We know of nothing smaller in nature than atomic objects—the atom and the electron. We cannot determine their properties by simply using our will-power. In the long run, we are compelled to measure the properties of atomic objects by means of the objects themselves. Under such conditions, the measuring instrument is indistinguishable from the object being measured.

But why can't we succeed in reducing the effect of one atomic object on the other in the process of measurement to some negligible value?

The fact is that both the instrument and the object are in the same quantum world and therefore obey all quantum laws. The main feature of quantum phenomena is their discreteness. Nothing happens very nearly or very slightly in the quantum world. Interaction takes place only by a whole quantum, a whole one or none at all. We cannot influence a quantum system "slightly". Up to a definite moment it will not react whatsoever to the action. But when the magnitude of the influence has increased sufficiently to affect the system, this occurs, as a rule, with a transi-

tion of the previous system to a new (also quantum) state, and frequently leads even to its destruction.

The process of observation in quantum mechanics resembles tasting rather than seeing. "The proof of the pudding is in the eating!" was a favourite proverb of the founders of quantum mechanics. Just as we cannot check again our impressions of the merits of a pudding after we have eaten it, so we cannot endlessly refine our data of a quantum system. It will be destroyed, as a rule, by our first measurement. Heisenberg was the first to understand this stern fact. Besides, he was able to write it down in the language of formulas.

However incomprehensible it may seem, the uncertainty relation is a simple consequence of the wave-corpuscle duality of atomic objects. At the same time this relation is the key to the understanding of the whole of quantum mechanics because its main features are concentrated in this relation. After Heisenberg's discovery it was necessary to revise the whole theory of cognition and not only atomic physics.

Again, only Niels Bohr was capable of taking this next step because he fortunately combined the powerful intellect of a genuine scientist with the philosophical nature of a true thinker. At one time he had created a system of images of quantum mechanics and now, fourteen years later, he carefully worked out its system of concepts. After Bohr's work it became clear that both the uncertainty relation and wave-corpuscle duality are only special manifestations of the more general *principle of complementarity.*

COMPLEMENTARITY PRINCIPLE

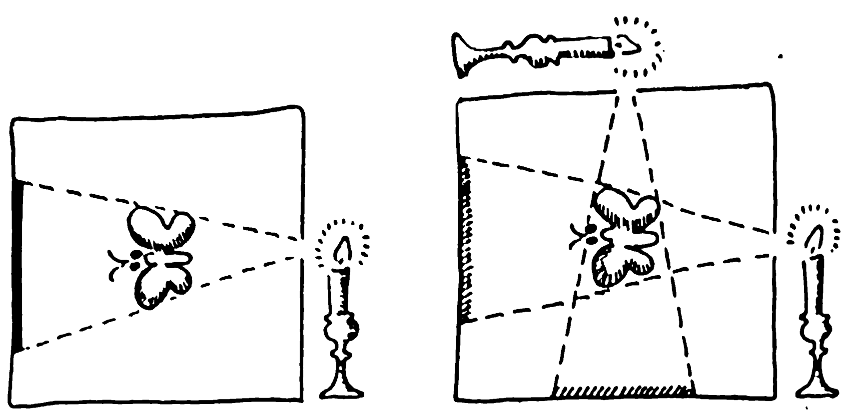
The principle that Bohr named complementarity is one of the most profound philosophical and scientific

ideas of our time, like the principle of relativity and the concept of a physical field. Its generality does not allow it to be reduced to any single statement; it must be mastered gradually by means of concrete examples. It is easiest to begin (as Bohr did) with the analysis of the process by means of which the momentum p and coordinate x of an atomic object are measured.

Niels Bohr noticed a very simple fact. The coordinate and momentum of an atomic particle cannot be measured simultaneously. Moreover, they cannot be measured at all with the same instrument. As a matter of fact, an exceptionally light mobile "instrument" is required to measure the momentum p of an atomic particle without changing it to any appreciable extent. But it is just this mobility that makes its position extremely indefinite. To measure the coordinate x we must use another and very heavy "instrument", one that would not even stir when struck by a particle. No matter how its momentum is changed in this case, we shall not even notice it.

When we speak into a microphone, the sound waves of our voice are converted into vibrations of a diaphragm. The lighter and more mobile the diaphragm, the more accurately it can follow the vibration of the air. But the more difficult it is to determine its exact position at each instant of time. This simplest of experimental apparatus is an illustration of Heisenberg's uncertainty relation. You cannot determine both characteristics of an atomic object—the coordinate x and momentum p—in the same experiment. Two measurements are required with two essentially different instruments whose properties complement each other.

Complementarity is the word and the change in the way of thinking that became intelligible to physicists thanks to Bohr. Up to his time physicists were sure



that the incompatibility of two types of instruments necessarily leads to inconsistency of the properties measured by them. Bohr denied such bluntness in inference and explained why. Yes, these properties are indeed incompatible, but both are equally required to provide a full description of an atomic object. Hence they complement rather than contradict each other.

The preceding argument on the complementarity of two inconsistent measurements can be explained by a simple analogy. Assume that you wish to find out what is inside a "black box" which has been designed in a special way, namely, like the camera obscura, or pinhole camera, shown in the illustration. In contrast to the ordinary camera, this one has two pinholes and, consequently, two photographic plates on the walls of the box opposite the pinholes. As long as the holes are closed, you know nothing at all about the article within the box; it simply doesn't exist as far as you are concerned. Opening the two pinholes alternately we shall obtain two plane projections of the article being studied on the photographic plates. Each of the projections taken separately is insufficient but both are equally necessary to reconstruct a three-dimensional picture of the article.

The two different projections of the article correspond to two different, complementary types of measurements in quantum mechanics. We cannot evidently

make both measurements simultaneously because if we open both pinholes of our camera at the same time we shall spoil the images on the two plates. In addition to the shadow thrown by the article by light admitted through the proper pinhole, light from the other, "complementary" pinhole will fall on each plate. It is likewise clear that in the first measurement-observation we shall disturb the initial state of the object, that is we shall displace and turn the article in the "black box". This means that when we open the second pinhole (after closing the first) we shall obtain a distorted projection on the second plate and not the true one. Under these conditions a three-dimensional picture can be reconstructed only with a certain error. But this is better, nevertheless, than a plane picture even if it is accurate.

Quantum mechanics contends that to reconstruct a "three-dimensional" picture of an atomic object two of its "plane projections", that is two complementary measurements, for instance of the coordinates and momentum, are quite sufficient.

Now if we translate this reasoning into the language of abstract concepts we shall obtain the following.

An atomic object is a "thing in itself" until we have indicated a method for observing it. Various properties of an object require different methods of observation which are sometimes incompatible with one another. Actually the concepts "object" and "observation" are only convenient abstractions required to describe the more general concept of an "experimental situation". Physical science studies concrete realizations of an experimental situation, which we call "phenomena" rather than objects by themselves. From the point of view of an experiment, any phenomenon is an ordered set of numbers, which are the results of measurement of the reaction of the object to the

action of an instrument of the selected type. Selecting different, complementary instruments we change the experimental situation. Realizing this situation we affect different characteristics of the object. Finally, by observing the consequences of this action, we obtain various sets of numbers, that is we study different phenomena. Although it is impossible to study complementary phenomena simultaneously, in a single experiment, they nevertheless characterize a single atomic object and are equally necessary for a complete description of its features.

A matter that has always been of importance is what kind of questions we ask nature. When we put questions to quantum nature we must be especially attentive because their selection governs the separation of nature into two parts, the system plus the observer. The complementarity principle maintains that at least two qualitatively different methods exist for separating an atomic phenomenon into the system and the observer.

These arguments about the complementarity of the properties of two incompatible instruments are an explanation of the principle of complementarity but are in no way exhaustive. In fact we need the instruments only for measuring the properties of atomic objects and not for their own sake. The coordinate x and momentum p are the *concepts* that correspond to two properties measured by means of two instruments. In the chain of cognition

phenomenon→ image→ concept→ formula

that we have already dealt with, the complementarity principle primarily affects the system of concepts of quantum mechanics and the logics of its inferences.

The point is that among the strict principles of formal logic there is one called the rule of the excluded

third which has it that of two contrary statements one is true, the other is false and there can be no third. Classical physics provided no grounds to doubt this rule since there the concepts of a "wave" and a "particle" were actually opposed and essentially incompatible. In atomic physics, however, both turned out to be equally applicable for describing the properties of the same objects and, to obtain a *full* description, it was necessary to use them simultaneously.

People brought up in the traditions of classical mechanics apprehended these requirements as something that coerced their common sense, and there was even talk of the violation of the laws of logic in atomic physics. Bohr explained that the point was the carelessness with which classical concepts were used without reservations to explain atomic phenomena, and had nothing whatsoever to do with the laws of logic. Such reservations are indispensable and Heisenberg's uncertainty relation $\delta x \cdot \delta p \geqslant {}^1/_2\, h$ is a precise expression of this requirement in the rigorous language of formulas.

The reason for the incompatibility of complementary concepts in our minds is a profound one but quite understandable. The point is that we cannot perceive an atomic object directly, by means of our five senses. Instead, we employ accurate and complicated instruments that have been invented comparatively recently. We need words and concepts to explain the results of our experiments, but they had been in use long before quantum mechanics was founded and are in no way adaptable for being used in quantum mechanics. We are compelled however to employ them; there is no alternative. We master our language and the principal concepts with our mother's milk and, in any case, long before we find out that such a thing as physics exists.

Bohr's complementarity principle is a successful attempt to reconcile the shortcomings of the established system of concepts with the advances in our knowledge of the world around us. This principle extended the potentialities of our thought by explaining that it is the way that the question of the essence of physical phenomena is put that is changed in atomic physics and not only the concepts themselves.

But the importance of the complementarity principle oversteps by far the limits of quantum mechanics where it first originated. Its true value for the whole system of human knowledge became evident only much later in endeavours to apply it in other branches of science. The admissibility of such a step is debatable, but it is impossible to deny the fruitfulness of this principle in all cases, even ones far from physics.

Bohr liked to give an example from biology concerning the life of a cell whose role is quite similar to that of the atom in physics. Just as an atom is the last representative of a substance that still retains its properties, a cell is the smallest part of any organism that still represents life in all its complexity and inimitability. To study the life of a cell means to find all the elementary processes that occur in it and to understand how their interaction leads to an entirely peculiar state of matter—to life.

But in an attempt to conduct our investigation according to this programme we find that such a combination of simultaneous analysis and synthesis is unrealizable. In fact, to penetrate into the details of the cell mechanism we observe it through a microscope, first an ordinary one and then an electron microscope; we heat the cell; we pass an electric current through it; we irradiate it and break it down into its components. But the more intently we study the life of a cell, the more we shall interfere with its functions and

with the natural processes occurring in it. This, finally, will destroy the cell and we shall not find out anything at all about it as an integral living organism.

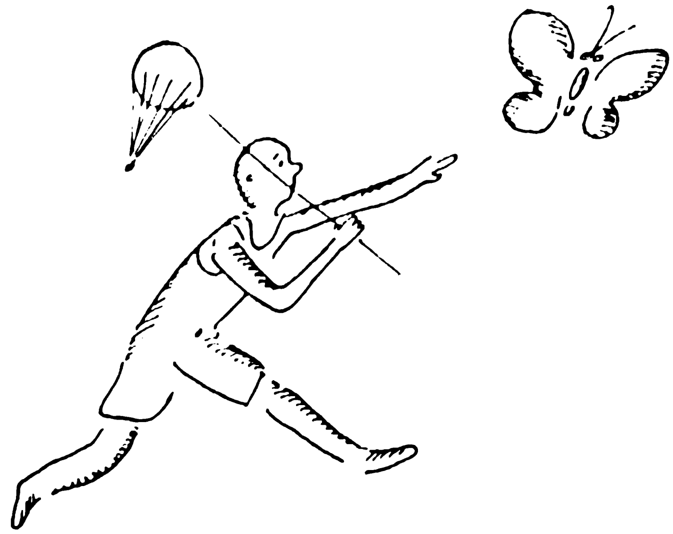
Nevertheless, to answer the question "What is life?" we shall have to employ both analysis and synthesis simultaneously. These processes are incompatible but not contradictory. They are only complementary in the sense Bohr used the word. The necessity of taking them both into consideration simultaneously is just one of the reasons why no complete answer exists as yet to the question on the essence of life.

As in a living organism, the important point in an atom is the integrity of its "wave-particle" properties. Besides begetting the finite divisibility of atomic *phenomena*, the finite divisibility of *matter* also led to a limit in the divisibility of the *concepts* by means of which we describe these phenomena.

It is often repeated that a properly put question is already half the answer. These are not simply fine words.

A properly put question is one about the properties of a phenomenon that it actually possesses. Therefore, such a question already contains all the concepts that are needed for the answer. An ideally put question can be answered concisely by "yes" or "no". Bohr showed that in reference to an atomic object the question "Wave *or* particle?" is put incorrectly. An atom does not possess such *separated* properties and, consequently, the question cannot be uniquely answered by "yes" or "no". In exactly the same way as there is no answer to the question "Which is the larger, a metre or a kilogram?" or to other similar questions.

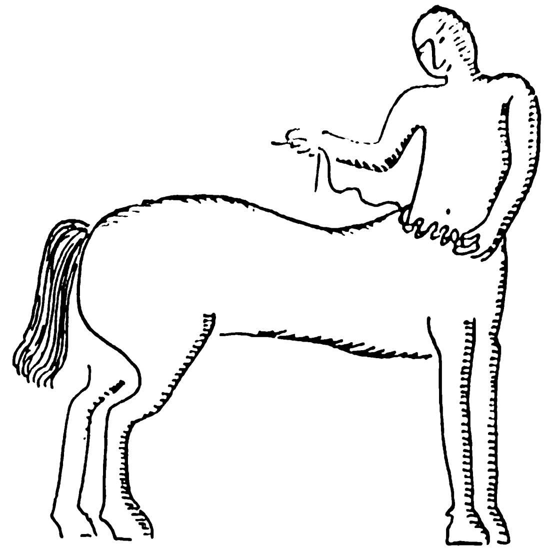
The two complementary properties of atomic reality cannot be separated without destroying the completeness and unity of the phenomenon of nature we call the atom. Such cases were well known in mythology.



You could not disjoin a centaur and keep both man and horse alive.

An atomic object is neither a particle, nor is it a wave, nor both simultaneously. An atomic object is *something entirely different* and not simply the sum of the properties of waves and particles. This atomic "something" is imperceptible to our five senses but is real, none the less. We have no images nor sensory organs enabling us to fully conceive of the properties of this reality. The power of our intellect, however, based on experiment, permits us to apprehend them without requiring additional senses or imagination. In the final analysis (and we must admit that Born was right) "... today the atomic physicist has left far behind the idealistic notions of the old-fashioned naturalist who hoped to fathom the mysteries of nature by catching butterflies in a meadow".

When Heisenberg discarded the idealization of classical physics—the concept of the "state of a physical system independent of observation"—he anticipated one of the consequences of the complementarity principle, since the concepts of "state" and "observation" are complementary in the sense of Bohr's proposition. They are incomplete when taken separately and hence can be defined only jointly, one by means of the other.



Strictly speaking, these concepts do not exist at all separately. We necessarily always *observe* some sort of *state* and not just something in general. And vice versa, each "state" is a thing in itself until we devise a method for its "observation".

Taken separately, the concepts of a wave, particle, state of the system and the observation of a system, are only certain abstractions that have no relation to the atomic world but are needed for understanding it. Simple classical pictures are complementary in the sense that a harmonic merging of these two extremes are required to obtain a full description of the nature of atomic phenomena. But within the limits of customary logic they can coexist without contradictions only if the range of their applicability is mutually restricted.

Bohr gave much thought to these and other similar problems, and he came to the conclusion that it is a general rule rather than the exception that *any truly profound phenomenon of nature cannot be defined uniquely by means of the words of our language, and requires at least two mutually exclusive, or incompatible, complementary concepts to define it.* This means

that under the condition that we retain our language and customary logic, thinking in the form of complementarity sets limits to the formulation of concepts corresponding to truly profound phenomena of nature. Such definitions are either unique but then incomplete, or they are complete but then ambiguous, since they include complementary concepts that are incompatible within the bounds of customary logic. Such concepts include those of "life", "atomic object", "physical system" and even the concept of the "cognition of nature".

It has long been known that science is only one of the methods of studying the world around us. Another—complementary—method is realized in art. The joint existence of art and science is in itself a good illustration of the complementarity principle. You can devote yourself completely to science or live exclusively in your art. Both points of view are equally valid but, taken separately, are incomplete. The backbone of science is logic and experiment. The basis of art is intuition and insight. But the art of the ballet requires mathematical accuracy and, as Pushkin wrote " ... inspiration in geometry is just as necessary as in poetry". They complement rather than contradict each other. True science is akin to art, in the same way as real art always includes elements of science. At their peaks they are indistinguishable and inseparable like the "wave-particle" properties in the atom. They reflect different, complementary aspects of human experience and give us a complete idea of the world only when taken together. Unfortunately, we do not know the "uncertainty relation" for the conjugate pair of concepts "science and art". Hence we cannot assess the degree of damage we undergo from a one-sided perception of life.

This analogy, like any other, is neither complete

nor rigorous. It can only help us to sense the unity and contradictoriness of the whole system of human knowledge.

ROUND AND ABOUT THE QUANTUM

DUALITY AND UNCERTAINTY

It has long been known in wave optics that you cannot see a particle in any microscope whatsoever if its size is less than one half of the wavelength of light by means of which it is illuminated. No one thought this strange; a wave of light exists by itself and a particle by itself. But when it was found that a particle could also be ascribed a wavelength, this statement of wave optics became the uncertainty relation: *a particle cannot localize itself with an accuracy greater than one half of its own wavelength*.

During the establishment of quantum mechanics even good physicists would joke bitterly that now they have to conceive of the electron as a particle on Mondays, Wednesdays and Fridays, and as a wave on the other days of the week.

"It is all rather paradoxical and confusing," wrote Davisson in 1928 in his famous article with the typical name "Are Electrons Waves?". We must believe not only that there is a certain sense in which rabbits are cats, but that there is also a certain sense in which cats are rabbits."

This method of thinking led to many paradoxes which can be avoided if we make it a point from the very start not to separate the "wave-particle" properties in the electron. Only this can convert Heisenberg's uncertainty relation from something strange and incomprehensible into a simple consequence of wave-corpuscle duality.

To satisfy oneself that this is so, let us conduct a thought experiment for measuring the momentum p of a flying particle of mass m. As we know, $p=mv$ and therefore it is sufficient for us to measure the velocity v. This is done by noting its positions x_1 and x_2 at the instants of time t_1 and t_2, and then computing the velocity by the formula

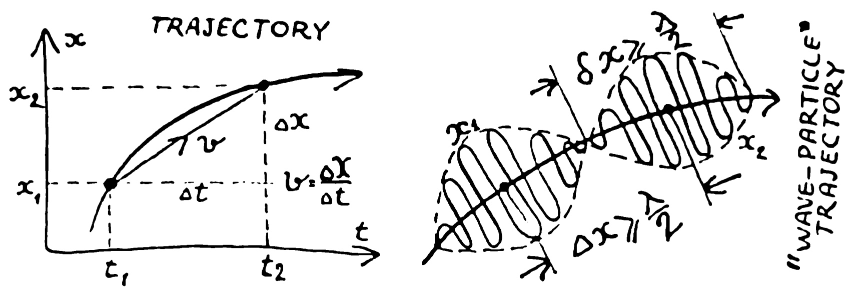
$$v=\frac{x_2-x_1}{t_2-t_1}=\frac{\Delta x}{\Delta t}$$

As always in making measurements, we influence the particle and thereby change its velocity. Consequently, if we wish to determine the velocity v as accurately as possible, we must select points x_1 and x_2 as close as possible to each other, i.e., pass over to the limit $\Delta x \to 0$. This is just exactly what we do in classical physics.

But in quantum mechanics we cannot select points x_1 and x_2 as close as we please. We must never forget that the flying particle is a certain wave process and not a point, and that we cannot conceive of it being smaller than half the wavelength of this process. Therefore, the error δx in determining each of the coordinates x_1 and x_2 is always greater or, in the limiting case, equal to $\frac{\lambda}{2}$.

For the same reason, there is no point in taking the distance $\Delta x=x_2-x_1$ less than $\frac{\lambda}{2}$. The most accurate value of the velocity v is obtained when $\Delta x=\frac{\lambda}{2}$, in which case $v=\frac{\Delta x}{\Delta t}=\frac{\lambda}{2\Delta t}$.

Of course, even this value includes a certain unavoidable error δv which depends upon the accuracy δx with which the coordinates x_1 and x_2 are determined



and equals

$$\delta v = \frac{\delta x}{\Delta t} \geqslant \frac{\lambda}{2\Delta t}$$

Comparing the last two formulas for determining v and δv, we come to the unexpected but strict conclusion that $\delta v \geqslant v$. Thus the error in determining the momentum is always greater or, at least, equal to its most accurately measured value. Thus $\delta p \geqslant p$.

The magnitude of the error δp is determined by the wavelength λ. As a matter of fact, de Broglie's formula $\lambda = \frac{h}{p}$ can be transformed to obtain $p = \frac{h}{\lambda}$. Since $\delta p \geqslant p$, then $\delta p \geqslant \frac{h}{\lambda}$. The magnitudes of the two errors

$$\delta x \geqslant \frac{\lambda}{2} \text{ and } \delta p \geqslant \frac{h}{\lambda}$$

depend upon the wavelength λ of the particle. The slower the particle travels, the longer its wavelength $(\lambda = \frac{h}{mv})$ and the less the error δp. The uncertainty of the coordinate δx is especially great for precisely such a particle. By varying the velocity of the particle we can reduce either δx or δp, but we can never reduce their product $\delta x \cdot \delta p \geqslant \frac{1}{2} h$.

Our analysis leads to still another unexpected conclusion which, incidentally, we already know. Atomic objects have no trajectory since, in calculating the velocity $v = \frac{dx}{dt}$ of a particle it is impossible to pass over to the limit $\Delta x \to 0$, $\Delta t \to 0$ and to calculate the derivative

$$x = \frac{dx}{dt} = \lim_{\Delta x \to 0} \frac{\Delta x}{\Delta t}$$

This is from the theoretical point of view. The first to run into this circumstance experimentally was Jean Perrin in his study of the Brownian motion. He wrote in this connection:

"The zigzags of the trajectories are so numerous and they are run through at such a high speed that it is impossible to keep your eyes on them ... . The mean apparent velocity of a particle during a definite interval of time undergoes immense changes in magnitude and direction, and does not approach any limit whatsoever when the interval is shortened. This is readily evident if we note the positions of a grain on the screen after each minute, then after each five seconds, and finally by photographing them at intervals of $^1/_{20}$ second ... . At no point of the trajectory can you obtain a tangent of definite direction. One finds difficulty in this case of resisting the idea of functions which have no derivatives, and which are wrongfully regarded simply as mathematical curiosities. Actually, nature suggests a conception of them equally with the idea of functions which have a derivative."

Fifteen years later, Perrin's guess was confirmed by Norbert Wiener, the founder of cybernetics, who developed a theory of the Brownian motion based on "continuous functions having no derivatives".

Of course, the Brownian motion is not yet quantum mechanics, and yet it is a good illustration of some of its features.

A POET AND THE COMPLEMENTARITY PRINCIPLE

In itself, the principle of complementarity, without reference to physics, is an ancient invention. Essentially, it is quite a well-known category of dialectic logic and has been repeatedly proposed by various philosophers down through the ages. Aristotle said, for instance, that "harmony is a blending and combination of the opposites" and Hegel's triads can be expediently adapted for analysing the concepts of quantum mechanics.

It is interesting to recall in this connection how the principle of complementarity was rediscovered by poets for their own purposes. In 1901, Valery Yakovlevich Bryusov wrote an article called "The Truth" in which we find the following:

"Whatever our world outlook (Weltanschauung), there are fundamentals which are, without doubt, compulsory in the process of thinking.... When I begin to think, I must ... believe that I, or any human being for that matter, can reach the truth by means of thought. There may be, and probably are, other ways of comprehending the world, such as dreams, presentiments and revelations, but if for some reason or other I choose logical thinking, I am obliged to put my trust in it. Otherwise all reasoning becomes useless....

"Thinking requires plurality, irrespectively of whether it is a splitting of my ego or appears as something external. Thought and, more generally, life comes into being from the confrontation of at least two principles. A single principle is nonexistence; the unity of truth is no-thought. There would be no space if there

were no right and left; there would be no morals if there were no good and evil....

"Of value in truth is only what can be questioned. That 'there is a sun' is impossible to doubt.... This is truth but it is of no independent value. No one has need of it. No one would go to the stake for such a truth. More clearly speaking, it is not a truth but merely a *definition*. 'There is a sun' is only a special expression instead of 'Such an item I call the sun'.

"Truth acquires value only when it becomes a part of a feasible world outlook. But at the same time it becomes disputable; it is at least possible to argue it.... Moreover, a valuable truth necessarily has the right to the exactly opposite, corresponding truth. In other words, an opinion directly opposite to a truth is, in its turn, also true...."

It is evidently appropriate here to recall the words of Blaise Pascal who wrote: "All the principles of the Pyrrhonists, Stoics, atheists, etc. are the truth, but their conclusions are false because the opposite principles are also the truth".

It is amazing that many of Bryusov's ideas anticipate Bohr's statements almost word for word. It is not generally known that Bohr arrived at his principle of complementarity "from philosophy" rather than "from physics". The idea of complementarity matured in him from his youth under the influence of the Danish philosopher Kierkegaard. It became stronger and more precise with time, until finally it found worthy application in atomic physics.

In 1922, before the founding of quantum mechanics, Valery Bryusov, one of the outstanding poets of pre- and post-Revolutionary Russia, wrote the following poem published in his collection *Mea*. It speaks for itself.

THE WORLD OF THE ELECTRON*

It may well be that these electrons
Are worlds just like our very own,
With kings and scholars, arts and armies,
And memories of ages flown.

And atoms—cosmic systems, spinning
Around a central spinning sphere,
Where things are just like ours, but smaller,
Or nothing like what we have here.

Though small their standards, how distinguish
'Twixt their infinities and ours?
Like us they have their griefs and passions,
And arrogance no less than ours.

Their sages, too, their boundless world assuming
To be life's centre and its stay—
They haste to probe creation's essence,
Philosophize, as I do today.

---

* Translated from the Russian by Louis Zellikoff

Chapter Nine

SCHRÖDINGER'S EQUATION * THE Ψ-FUNCTION. THE SHAPE OF WHAT DOES IT PORTRAY? * THE ATOM * QUANTUM TRUTH

"A naturalist, leaving the region of direct sensual perception behind him with the aim of discovering more general interrelationships, can perhaps be likened to a mountain-climber who wishes to reach the summit of the highest mountain to view the locality lying before him in all its diversity. The mountain-climber must also leave the fertile populated valleys. As he ascends, he has an ever wider view of the neighbourhood but, at the same time, the signs of life about him become less frequent. He finally reaches a dazzling bright region of ice and snow where there is no more life, and breathing is almost impossible. Only by crossing this region can he reach the summit. But when the summit has been mounted, a moment comes in which the whole locality spreading out before him is clearly visible in its entirety. Then, perhaps, the sphere of life will not seem too far from him.... In previous ages these lifeless regions were apprehended simply as severe wastes whose intrusion seemed to be blasphemy with respect to some kind of higher powers that cruelly punish all who dare to draw near to them."

These words of Heisenberg are a good explanation of the qualitative leap that occurred in the minds of people when they passed over from the observation of phenomena that directly acted on their sensory organs to the study of atomic phenomena. This breakthrough occurred at the turn of the century, and it is so important that we shall illustrate it again by a concrete example.

Imagine that you hear a sound produced by a taut string before you. You hear the sound, see the vibrating string, and can touch it with your hand. On the basis of these data an *image* is formed in your mind of the physical *phenomenon* occurring before you. The *concept* of a "wave process" comes later upon observing other similar processes. To make this concept unique it is fixed with a *formula* which is an equation enabling the whole process of string vibration to be predicted beforehand. We can check this prediction by recording, for instance, the vibration of the string on motion picture film.

We have purposely traced the chain

phenomenon→ image→ concept→ formula→ experiment

once more. It is the basis of all physical knowledge. The last link in this chain, experiment, checks how correctly we imagine a phenomenon as a whole on the basis of our partial knowledge of it.

But this simple scheme will not help us to answer the question "What is an atom?" simply because the phenomenon "atom" does not affect our sensory organs and they cannot give us any, even an approximate, "image of an atom". This is why the concept of an "atom" first arose purely speculatively, without any references to the sensory organs. This is why it remained only a curious hypothesis for twenty centuries,

one that had no advantages whatsoever over other hypotheses on the structure of matter.

The real history of the atom began with the advent of science when people learned to trust the readings of instruments and not merely to rely on their sensory organs. They used instruments to observe how bodies behaved when they were being dissolved, when electric current was passed through the solution, when they were heated, illuminated and when subjected to many other types of action. Scientists *studied* these phenomena and not simply *observed* them. They *measured* the temperature of the bodies, the wavelength of the light they emitted and many other features about which we already know. They recorded the results of their measurements in the form of *numbers*. These were numbers that replaced the direct sensations furnished previously to the physicists by their sensory organs. A *number* was the only thing they came to trust when they began to study phenomena inaccessible to their direct perception. With numbers on hand they began to find relations between them and to write down these relations in the form of *formulas*.

But people communicate by means of words and not formulas, and to tell about the new relations they had found in nature they had to evolve concepts that would correspond to the formulas. Sometimes these concepts are very extraordinary but people become accustomed to them, learn to apply them correctly and even create some kind of images for themselves that they associate with the new concepts.

This reverses the chain of cognition

phenomenon   image ← concept ← formula ← experiment

This revised chain can readily be traced in the history of the atom. Fraunhofer, Kirchhoff and Bunsen

discovered that each atom emits a strictly definite set of spectral lines (the phenomenon) and each spectral line corresponds to a number—the wavelength λ (the experiment). Balmer, Rydberg and Ritz found simple relationships (the formula) between these numbers, and Bohr showed that their formulas follow from a single principle which was named quantizing (the concept). Finally, on the basis of these experiments, formulas and concepts, an image—Bohr's atom—was developed.

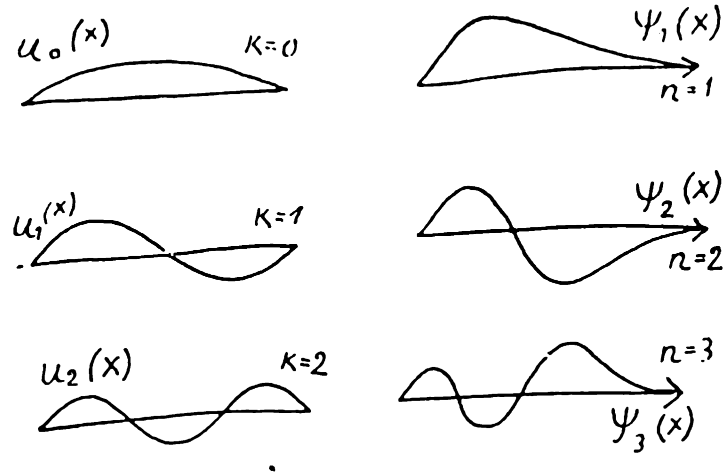
But experiments were continued, and they produced new numbers and new facts which could no longer be accommodated by the previous formulas, concepts and images. Then quantum mechanics was developed, which is a unified principle from which all the earlier empirical formulas and successful guesses followed.

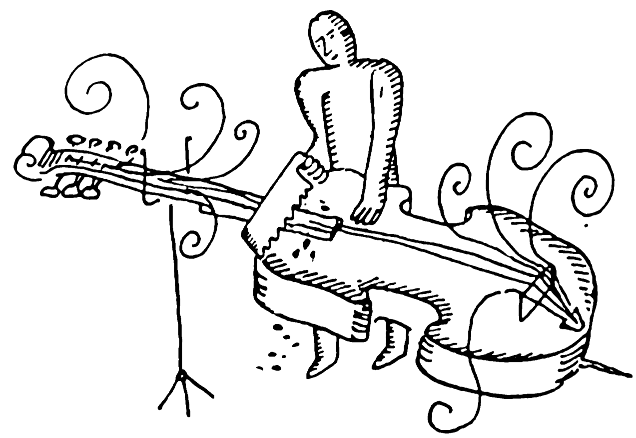
Thus far we have found out quite a lot about the experiments of atomic physics and the concepts it is necessary to employ to explain these experiments. But ours is a higher aim. We want to develop an *image of the atom* on this newer, higher level of knowledge. To do this we must concern ourselves, at least cursorily, with the formulas of quantum mechanics. This is a necessary condition; in the long run, the beauty of logical constructions in science is much more important than the effects of unexpected associations.

SCHRÖDINGER'S EQUATION

The preceding accounts about quantum mechanics should almost have convinced us that the electron has no definite position in the atom, nor even some kind of orbit along which it travels. In return we have thus far mastered the quite vague idea that the electron becomes "blurred" in its motion in the atom.

Schrödinger succeeded in expressing this indefinite





idea very precisely in the unambiguous language of formulas. As any other profound law of nature, Schrödinger's equation cannot be strictly derived from simpler ones. It can only be guessed. That is just what Schrödinger did and later he admitted that he still didn't understand how he had done it. But after the equation has been guessed, we must learn to apply it, to find out what all the symbols mean and what phenomena in the atom they represent. We have already cited Schrödinger's equation

$$\frac{d^2\Psi}{dx^2} + \frac{2m}{\hbar^2}[E - U(x)]\Psi = 0$$

once and explained the symbols it contains: $\hbar$ is Planck's constant h divided by 2π, m is the mass of

the electron, E is the total energy of the electron in the atom, and $U(x)$ is its potential energy which shows with what force the electron would be attracted to the nucleus if it was a particle at a distance x from it. But the meaning of the wave function psi (Ψ) still remains obscure. To clear it up let us return again to the analogy with the vibrating string. Its equation

$$\frac{d^2u}{dx^2} + \left(\frac{2\pi}{\lambda}\right)^2 u = 0$$

is much like the Schrödinger equation. Several solutions of the string equation, the function $u = u_k(x)$, are shown in the illustration. These are ordinary, well-known sine curves and their meaning is obvious. They depict the *shape of the string* at some instant of time; the illustration is thus an instantaneous photograph of its vibration process. The shape of the vibrating string depends upon the number k of nodes which are points that remain stationary in the vibration process. Therefore, there are an infinite number of solutions $u = u_k(x)$ which differ in the number of nodes k.

Now look at the drawing where alongside the string sine curves $u_k(x)$, the solutions $\Psi = \Psi_n(x)$ are shown of the Schrödinger equation for the hydrogen atom. The two sets of curves are rather alike. Even if no real vibrations similar to the motions of the string occur in the atom, this does not make the analogy less useful.

The noted analogy enables the solutions $\Psi_n(x)$ to be numbered with the integer n in the same way as the solutions are numbered by the integer k. Moreover, it was found that the whole number n was the same incomprehensible *quantum number* by means of which Bohr numbered the electron orbits in the atom. Now it had lost its mystic shade of meaning. The integer n is none other than the number of nodes of the wave function increased by unity ($n = k + 1$).

By a certain "will-power" Bohr's first postulate ordered electrons to travel only along those orbits in an atom that comply with the quantum condition

$$mvr = n\frac{h}{2\pi}$$

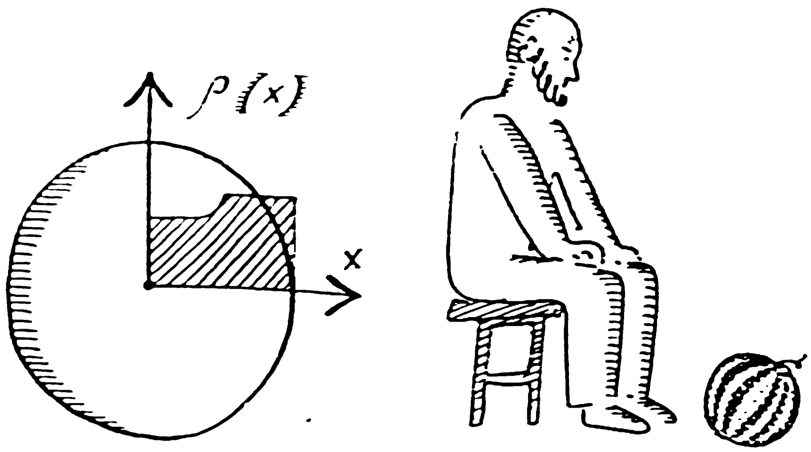
This was a fruitful principle but one unnatural for physicists. It provoked a complicated mixture of delight and discontent in his contemporaries. Schrödinger's requirements are much more natural. However slyly the electron moves in the atom, it must, nevertheless, be located *inside* the atom. Consequently, the Ψ-function which "represents" this motion must be concentrated near the nucleus regardless of the nature of this function. This single *boundary condition* allowed all the other factors, such as Bohr's quantum conditions, the electron's energy on the stationary orbits and the meaning of the quantum numbers, to be derived from Schrödinger's equation.

In its time, these consequences of Schrödinger's theory won over many physicists owing to its simplicity. They put their trust in Schrödinger's equation and began to clear up its puzzling features. What, they wanted to know, does this function Ψ represent in itself?

If the function $u_\kappa(x)$ depicts the shape of the vibrating string, what does Ψ depict?

THE Ψ-FUNCTION. THE SHAPE OF WHAT DOES IT PORTRAY?

This is one of the most difficult questions of quantum mechanics and one which even Schrödinger answered incorrectly at first. But his answer was so con-



venient and so close to the truth that we shall make use of it for the time being. He reasoned as follows.

The electron does not exist in the atom as a particle. It is spread out into a certain cloud. The shape and density of this cloud are determined by the wave function $\Psi(x)$. *At the distance* x *from the nucleus the density* $\rho(x)$ *of the electron cloud is equal to the square of this function. Thus*

$$\rho_n(x) = |\Psi_n(x)|^2$$

To explain this idea, let us again recall the same watermelon with which we began our account of quantum mechanics. We shall try to plot the curve of its density $\rho(x)$ against the distance x to the centre of the watermelon. Evidently, the function $\rho(x)$ is approximately constant throughout; it only increases slightly near the outside due to the seeds and rind, and finally drops sharply at the boundary of the watermelon. Even a person that has never seen a watermelon can schematically picture how it is arranged inside by looking at our diagram. True, he will not have the faintest idea of its taste, colour or fragrance, as well as of a thousand other minor features that distinguish one watermelon from another.

In our attempts to penetrate into the atom we find ourselves in the position of a man who has never seen a watermelon but wishes to picture one by using the

function $\rho(x)$. The function $\rho(x)$ is calculated for an atom from Schrödinger's equation and is then used to plot the distribution of the electron cloud in the atom. The pictures thus obtained substitute for the visual image of the atom that we are all unconsciously striving for.

Shown on pages 264 and 265 are three-dimensional representations of an atom of hydrogen, plotted from the functions $\rho_n(x)$ which were calculated by Schrödinger's equation. This is the new image of the atom we have been so long in getting to and to which we should now become accustomed. The image we have built up will change only slightly in the following. To be more exact, it is our attitude toward it and not the image itself that will change.

Now the most difficult barriers have been surmounted and we can sum up our acquired knowledge without haste. First of all, and now on a new level, we shall return again to the question "What is an atom?"

THE ATOM

Recall Thomson's "plum-pudding" model of the atom. He visualized it as a large positively charged sphere in which small negatively charged electrons are distributed.

Actually, everything turned out to be exactly the other way round. Located at the centre of the atom is a very small positively charged nucleus surrounded by a negative cloud of the electron. The shape of this cloud is not arbitrary; it is determined by the precise laws of quantum mechanics. This is not, of course, a sphere with sharply defined boundaries, but as a whole an unexcited atom of hydrogen is very much like a sphere (this guess of Democritus' was correct).

The shapes of excited atoms, however, are not sphe-

rical and the more strongly the atom is excited the less it resembles a sphere.

In exciting an atom we expend energy precisely for rearranging its electron cloud. Each shape of the cloud corresponds to its entirely definite amount of energy. Hence, to transform the atom from one shape to another we must expend a strictly measured-off amount of energy, the quantum $h\nu$, as required by Bohr's second postulate.

Thus far we have intentionally spoken only about the hydrogen atom. This, essentially, is the only atom that the physicist now knows about in great detail and of which he can conceive a likely image. Now this is more or less evident to everybody, but in the first years after the founding of quantum mechanics, the enthusiasm of the victors was so great that they entirely forgot about the ancestress of the atom—chemistry. "From the point of view of a physicist, chemistry does not exist," declared the keenest of them. "Just give us the charge of the nucleus, and we will dress it up with a coat of electrons so that nobody can distinguish the atom we have built from a real one."

They began to build their atoms but found that they could not manage without chemistry. As simple an atom as lithium proved to be the first stumbling block. Instead of arranging two electrons in the first shell and the third in the second shell, they put them all in a single shell. But in the years of upsurge individual difficulties are soon overcome.

A way out was found almost immediately after referring to Mendeleev's periodic system of elements which had many a time come to the aid of physicists and chemists. Indeed, if the chemical properties of elements depend on electrons surrounding the nucleus, then the periodicity of these properties indicates that the electrons must be arranged not randomly but in groups, called shells. It was quite logical to assume that the number of electrons in each shell coincides with the length of the periods of Mendeleev's table. That is just what Wolfgang Pauli assumed.

Only then did it become possible to develop the images of atoms more complex than that of hydrogen. As a whole, the shape of the electron cloud in the heavy atoms does not differ greatly from that in our drawings. But it could be computed only after the work done by Douglas Hartree and the Soviet physicist Vladimir Alexandrovich Fock. This is a very complicated problem and sometimes beyond the powers of even up-to-date electronic computers.

In speaking of the shapes of bodies we assume, as a rule, that they also have dimensions. This is not always true. A billiard ball has both shape and size, but it is difficult to speak of the dimensions of a cloud although its shape usually raises no doubt.

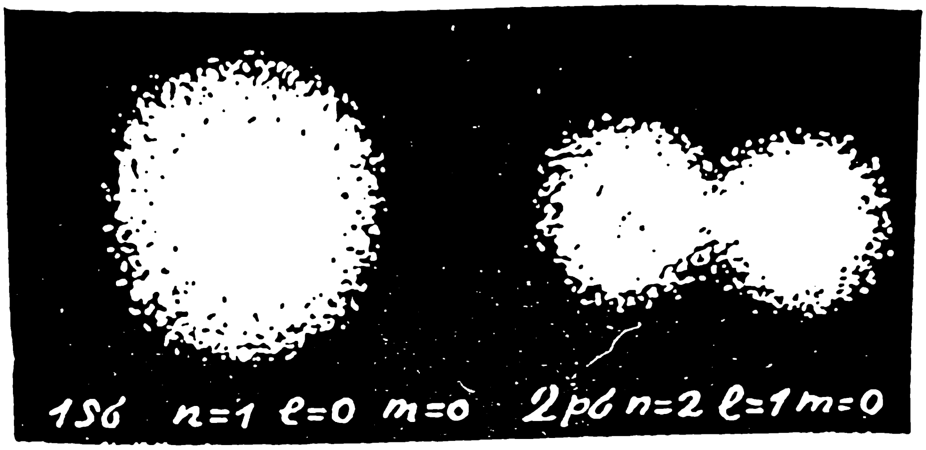
The most unexpected consequence of the new model of the atom is that it has *no definite geometrical dimensions*. In other words, the boundary of the atom just as the outline of a cloud for that matter can be

defined only nominally. We are compelled to accept this consequence of the new model in order to explain certain observed properties of bodies, for instance, the diversity of geometrical shapes of crystals. This should not astonish us particularly. Houses are built of bricks, but we do not consider it strange that a brick is simply a brick and not a miniature house. Bodies surrounding us have colours, odours and dimensions, but the atoms of which these bodies are made have none of these qualities. Only one invariable property remains to them, that of mass. There is no such thing as invariable shape. Invariable are only the laws of quantum mechanics which govern this shape.

But why is the atom, which does not even have dimensions, so stable? This also should not astonish us. After all, the earth doesn't rest on three whales but nevertheless, poised in the void, it has kept its orbit invariable for millions of years. The secret of its stability is in its motion and in the invariability of the dynamic laws that govern this motion. This is the same reason for the stability of atoms although the laws that control the motion of electrons are not at all like those of celestial mechanics.

(It should be said in all fairness that quantum stability is much more reliable than the dynamic stability of classical mechanics. The structure of a destroyed atom is restored but the orbit of the earth will never again be the same if it is once disturbed by the sudden intrusion of some foreign body from outer space.)

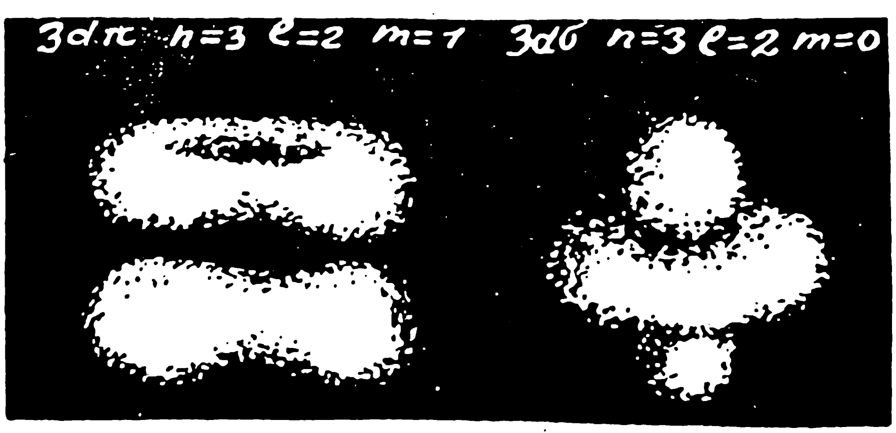
The atoms of various elements differ from one another by the mass and charge of their nucleus. But by what feature can we distinguish two atoms of the same element? With respect to watermelons such a question is needless. Nobody has ever seen two exactly identical watermelons. It is much harder to distin-

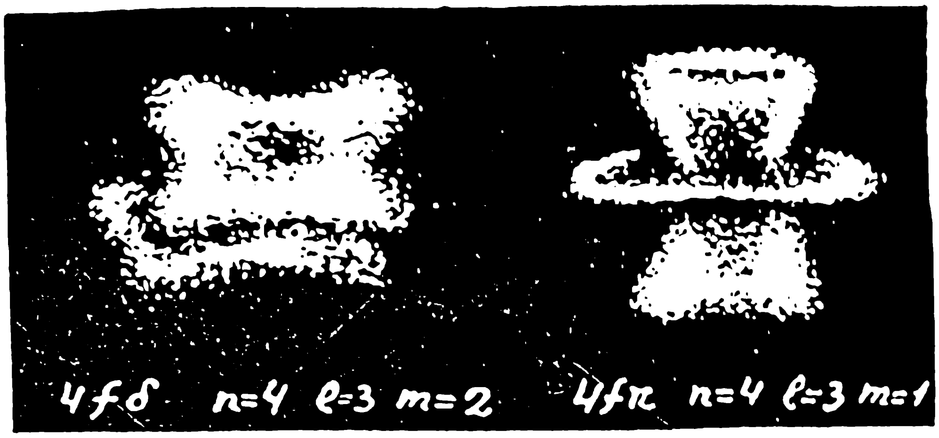


guish one brick from another, unless they are broken bricks, in which case the task is somewhat simplified.

The same is true of atoms. If the mass and charge of their nuclei are equal, they can only be distinguished by the shape of their electron cloud which depends upon the degree of excitation of the atoms. Two atoms can be distinguished only if one of them is excited. All unexcited atoms of the same element are indistinguishable from one another, like bricks made from the same mould. The role of such moulds for atoms is played by the dynamic laws of quantum mechanics which are invariable and identical for all atoms.

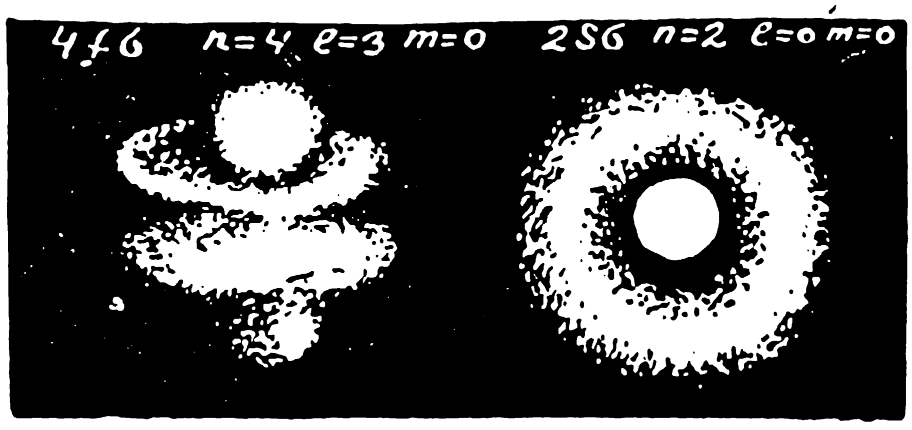
The portraits of the atom in the illustrations represent our present level of knowledge about it. This is the up-to-date image of the atom that has superseded the models of Democritus, Thomson and Bohr. Of course, these "portraits" should not be understood





too literally; they are by no means "photographs of atoms" like the photographs of a vibrating string. Neither simple nor complex instruments can directly measure the distribution of electron density within the atom because they will inevitably destroy it (even a watermelon must be cut open to make sure that it is ripe). All the same, we have good cause to believe in the picture that has been found. By its means we can consecutively explain all the experiments that have led to the present image of the atom.

We should no longer be surprised that the alpha particles in Rutherford's experiments flew unimpeded through billions of atoms as through a void. When passing through the tails of comets the earth is never deviated from its orbit. The mechanism by means of which spectral lines are produced should also be clear to us now. The atom simply changes the shape of its



electron cloud distribution in a jump, emitting a quantum of energy. We should now understand the splitting of the frequency of spectral lines in an electric field (Stark effect) and in a magnetic field (Zeeman effect). The electron field is charged and its various shapes change slightly under the influence of the fields. Likewise changed are the energy of the quantum required to transform the cloud from one shape to another and the frequency ν of the spectral line to which this quantum corresponds. Using the equations of quantum mechanics these simple qualitative arguments can be confirmed by strict calculations, and it can be shown that they coincide with the experimental data.

But right now it is more important for us to look into another matter. Why are we sure that the image of the atom we have developed is the true one?

QUANTUM TRUTH

First of all, what kind of truth are we to discuss? What do we understand to be the truth in quantum mechanics? If we were talking about a watermelon, the question would be settled quite simply. We would say, for instance, that a knowledge restricted to the density distribution inside the watermelon would be insufficient. This is by far not the whole truth about watermelons. Only when we see, touch and finally eat one can we say what it actually is. But what constitutes such full knowledge in the opinion of the majority of people is very provisional for scientists. They will begin by examining the watermelon under a microscope and say that it consists of cells. Somewhat later they will declare that the cells are built of molecules, and then that the molecules consist of atoms. We have completed the circle. To find out everything there is

to be known about a watermelon we must again answer the question "What is the atom?".

Actually, the matter is not as complicated as it would seem. The concept "watermelon" was developed many centuries before any science was known and, since it is based only on our sensations, it does not depend on any past or future scientific achievements. This concept can change only if a new, sixth sense appears suddenly in everybody. Assuming this to be unreal we lightheartedly assert that we know all the truth about a watermelon if we put it to the test of our five senses. (Remember how you yourself buy a watermelon. First you select a likely one from the heap, then you take it in your hands, sometimes you hold it to an ear to hear the slight crackling sound it makes when you squeeze it, and finally you cut out a small wedge to taste.)

Can we approach the concept of the "atom" with the same measure? The number of experiments on whose basis we develop the image and concept of the "atom" is infinite and each one, in principle, adds something new to our knowledge. We cannot stop all of a sudden and say "No more experiments. We have already developed an image of the atom for ourselves and further experiments can only spoil it". On the contrary, we rejoice in each new experiment and especially those that do not fit into the limits of the images we ourselves have formed. These are just the kind of experiments that enabled us to reject the idea of atoms being solid spheres and to devise a more refined model. Why are we sure now that the present image of the atom is the true one?

We must admit that this is something physicists are not at all sure of. They can, however, say honestly and with dignity, "Not a single experiment, conducted in the last hundred years, contradicts the picture

we have created. Hence, it is better to speak of its fruitfullness rather than its truth, about how well it helps us explain and predict the distinctive features of atomic phenomena".

Here a startling fact comes to light. We find that it isn't so necessary for us to know "just how an atom actually looks". It is sufficient for us to learn the equations of quantum mechanics and the rules for dealing with them. Then we can predict everything: how the colours of a body will change when it is heated, what spectral lines it will emit, and how their wavelength will change if we place the body in an electric or magnetic field. We can predict the shape of crystals, their specific heat and conductivity. Finally, we can build nuclear power stations and atomic ice-breakers for our Arctic Ocean fleet, and they will work excellently. And all of this without the slightest reference to the "true" shape of the atom.

On these grounds (following Heisenberg's example), many physicists have proposed that quantum mechanics can do without any visualizable images whatsoever. The expedience of such an extreme can be disputed, but it is impossible to deny it unconditionally. The supporters of extreme views answer the question "What is an atom?" laconically: "The atom is a system of differential equations." To our regret, there is much truth in this jest. In comparison with a whole watermelon, an "atom of a watermelon" is very meagre in properties. Even the properties it has are contradictory and so far they can be combined together without committing violence upon logic and common sense only in the equations of quantum mechanics.

Quantum mechanics is a mathematical scheme which enables physically measurable characteristics of atomic phenomena to be calculated. Such phenomena include the energy levels of atoms, the intensity and

frequency of spectral lines, their splitting in electric and magnetic fields, and much, much more.

If this alone were the aim of physics, the development of the mechanics of the atom could be considered to be completed. The mission of physics, however, is more far-reaching. It should give us a rational picture of the world we live in. It is impossible to accomplish such a widespread programme with formulas and numbers alone. We must also find images and formulate suitable concepts. This is of especial interest to non-physicists who neither know nor understand the formulas of quantum mechanics. The language of images and concepts is the only method by which they can penetrate into the depths of the atom. Since the times of Democritus we have advanced a great distance along this road and have drawn for ourselves a more or less satisfactory picture of the atom, and to attain perfection, several final touches are still lacking.

We now know that "wave-particle" duality is the principal property of all atomic phenomena. But, by itself, is not the electron a particle? Now we have run to the other extreme and maintain that the electron in the atom is a certain kind of charged cloud. Such a picture is convenient for understanding the majority of experiments but it cannot explain, for instance, the photoelectric effect. Indeed, no one has ever seen a piece of electron cloud being emitted from an atom. It is always a single and indivisible electron. How then are atomic clouds of different shapes always collected instantaneously into the single and same indivisible particle?

To answer this question we shall have to introduce a new concept, that of *probability*. It is a fundamental concept, so much so that without it modern quantum mechanics does not exist at all. Now we shall deal with it.

THE LIFE OF BOSCOVICH...

Roger Joseph Boscovich (1711-1787) is known now only to a narrow circle of specialists, but at the beginning of last century he was famous, and his theory of the atom influenced the outlook of such scientists as Faraday and Maxwell.

Boscovich was born and spent his childhood in what is now Dubrovnik on the Dalmatian coast (it was then called Ragusa). He was the eighth of nine children and the youngest of six sons in a family of well-to-do merchants. This was a time when any vocation was of significance and generally recognized only if it was sanctified by the Church or associated with it. From his eighth year Boscovich studied in the local Jesuit College and when he was 14 his parents sent him to Rome, his mother's native city. He served for two years as a novitiate and was then accepted in the Collegium Romanum to continue his studies for the priesthood. His best-liked subjects were mathematics, physics and astronomy in which he excelled. In 1736, he published his first paper on the sun's equator and period of rotation. At the age of 29 he held the chair of mathematics at the Collegium and four years later became a priest and a member of the Society of Jesus. For fourteen years he taught physics and mathematics, and conducted research in the aberration of light and the shape of the earth. He also mapped the Vatican City.

Boscovich was a scientist and a poet as well. (In 1779, he dedicated a poem to Louis XVI in which he forecast him a reign devoid of solar eclipses.) The brilliant qualities of his versatile nature won him admission into the most eminent church, academic and diplomatic coteries of the continent.

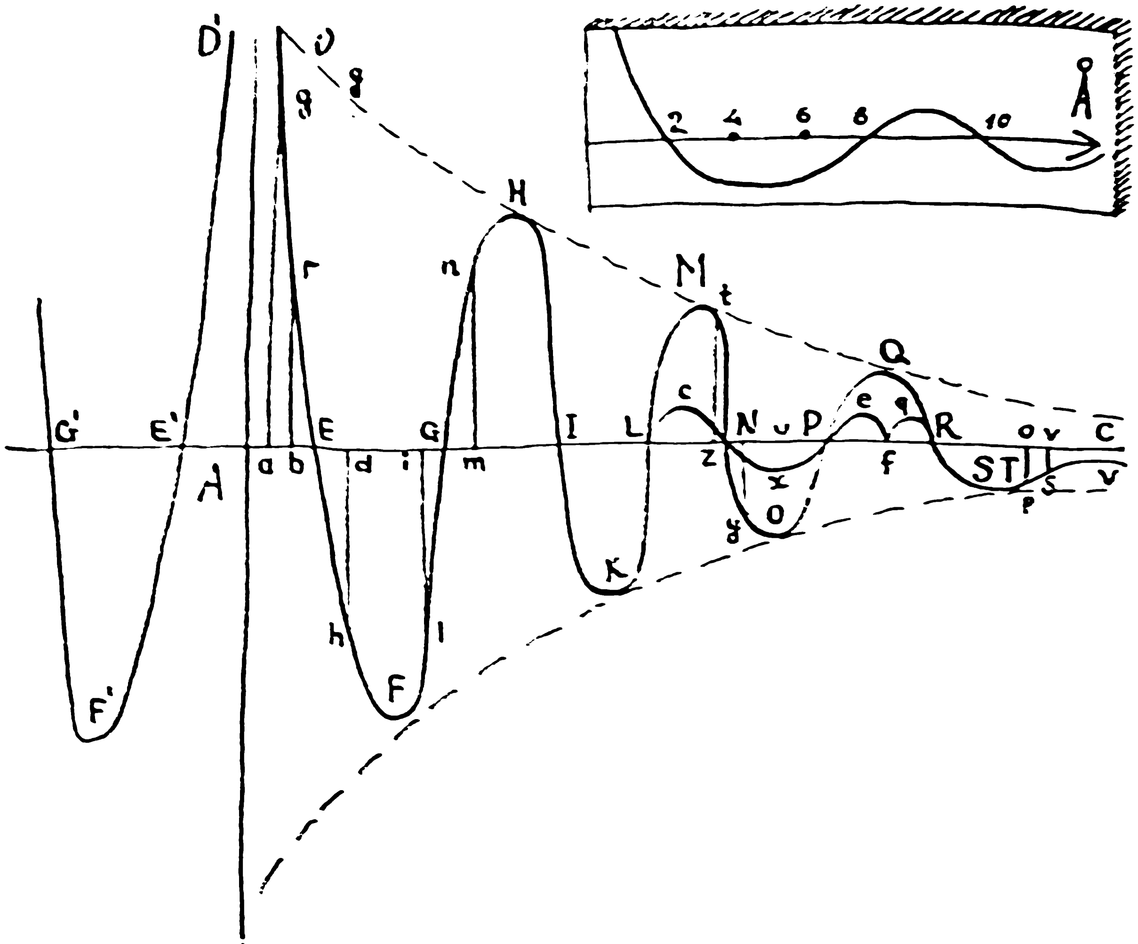
In 1757, he went to Vienna as a member of the embassy and there, during a period of eleven months, he wrote his *Theoria Philosophiae Naturalis* which he had been turning over in his mind for twelve years. On his return from Vienna he set out on a four-year tour of Paris, London and Constantinople. Then he lectured, worked in the Milan observatory, gained the hatred of his colleagues due to his independent views, and in 1772 he found himself in Venice with no means. His friends obtained a post for him in Paris where he lived for ten years and returned to Italy only in 1783 to publish his collected works. At the end of 1786, he felt symptoms of mental disorder which soon became pathological melancholia. After attempting suicide he became insane and on February 13, 1787 was finally delivered of all the complications of his life.

... AND HIS ATOM

Of the few people that did believe in atoms in the eighteenth century, Boscovich was the only one who did not believe that atoms were tiny solid spheres. Consequently, his ideas are closer to us than all the atomic theories of the nineteenth century.

Boscovich based his disbelief of incompressible atom-spheres on the fact that it is impossible with such atoms to explain the crystalline structure of bodies and their elasticity, the fusion of solid substances, the evaporation of liquids and, all the more, the chemical reactions between substances allegedly made up of such round, hard, and impenetrable spheres.

Boscovich conceived of the atom as being the centre of forces that vary with respect to their distance from this centre. Near to the centre the forces are repulsive. This corresponds to the repulsion of atoms when they are brought into close proximity or collide. As we mo-



ve away from the centre, the repulsive force is first reduced, then becomes zero, and is finally transformed into an attractive force. Exactly at the instant when the force is reversed, Boscovich contended, all liquid and solid bodies are formed. But if we move still farther away from the centre, the forces again become repulsive ones. This is the instant when liquid bodies evaporate. Finally, at a long distance from the atom, the forces are always attractive as required by Newton's law of universal gravitation.

Thus each of Boscovich's atoms "extends to the very boundary of the solar system". Since centres of forces can be neither destroyed nor created, the atoms of Boscovich were eternal, just as those of Democritus. This particular part of Boscovich's teaching was especially dear to Faraday. We can readily perceive its analogy with the ideas of Faraday on the lines of force of an electromagnetic field.

Boscovich's atom is considerably nearer to the modern atom than was that of Democritus. For example, like the modern one it has no definite geometrical dimensions. But with its aid we can understand the diversity of shapes of crystals and all kinds of chemical transformations in which these atoms participate.

Look at the diagram taken from Boscovich's book. It represents the law of variation of the forces as he imagined it to be. Of course, the atom of Boscovich is only a speculative scheme based neither on experiment nor on mathematics, but only on common sense and on intent observations of nature. Boscovich wrote: "There are indeed certain things that relate to the law of forces of which we are altogether ignorant, such as the number and distances of the intersections of the curves with the axis, the shape of the intervening arcs and other things of that sort; these indeed far surpass human understanding, and He alone, Who founded the universe, had the whole before His eyes."

The second and smaller diagram shows the law of variation of forces acting between two atoms of hydrogen. It is amazing how much it resembles the diagram drawn by Boscovich. But *this* law has been calculated from equations of quantum mechanics without any arbitrariness or reference to divine providence. By means of this law of forces we can predict the spectrum of a molecule of hydrogen, calculate the energy beforehand that must be expended to tear one atom of hydrogen from the other; we can foresee what will happen if we mix hydrogen with chlorine, for instance, and what changes will occur if we irradiate the mixture with ultraviolet rays.

Quantum mechanics enables us to derive the law of the variations in the forces between any two arbitrary atoms. In principle, it is capable of calculating the shapes of crystals. It can even predict the colour of

chemical compounds. You can do all these things, of course, only if you have mastered the quite complicated mathematics of atomic physics. Anyone, however, who is at least slightly acquainted with its images can readily understand many of the features of the structure and properties of matter.

PAUL EHRENFEST (1880-1933)

In addition to its prophets, science has need of its apostles as well. Besides solitary geniuses that alter its course, science needs devotees that keep its fire alight and are capable of kindling it in the hearts of neophytes. Such people create an atmosphere of intellectual festivity and spiritual enthusiasm in which talents blossom swiftly and gifted minds find fertile soil to apply their efforts. Scientists of this rare type were Arnold Sommerfeld of Germany, Paul Langevin of France, and Leonid Isaakovich Mandelstam in Russia.

Paul Ehrenfest was also such a man. He was born and raised in Vienna, studied in the Vienna University under Boltzmann and then in Göttingen under Felix Klein. After finishing his education he lived for five years in Russia and then, in 1912, at the request of Lorentz, he accepted the chair of physics at the University of Leyden, previously held by Lorentz. Here, every Tuesday, for twenty years, he held a seminar at which all the eminent and famed scientists, who had rebuilt the very foundations of physics in a fourth of a century, told about their latest works.

The hypothesis of electron spin was born and became firmly established at this seminar, and Ehrenfest was its midwife and godfather. He was the initiator and organizer of the famous polemics between Bohr and Einstein. He lived in the centre of the "phy-

sical events" of his time and did much to implement their successful completion.

Ehrenfest was a man of rare cordiality. Everyone was fond of him. Bohr, Planck, Heisenberg, Pauli, and Schrödinger paid him frequent visits. Einstein wrote him, "We were created by nature for each other. I have an even greater need of your friendship than you have of mine". But something broke his spirit and on September 25, 1933, he committed suicide.

Paul Ehrenfest endowed science with certain physical ideas which have outlasted the living memories of his students and friends. He bridged the chasm which in the minds of his contemporaries separated quantum phenomena from classical ones. The essence of the theorems he proved consists in the following.

We have repeatedly asserted that the equations of quantum mechanics entirely differ from those of classical mechanics. Therefore the motion of quantum objects can neither be described nor represented by classical terms and images. In approximately the same way it is impossible to indicate on a terrestrial globe all the movements of a passenger crossing the Atlantic on an ocean liner. But, regardless of how the waves rock the ship and whatever the passenger is occupied with during his voyage, on the average he nevertheless travels along the set course.

Something similar is true of the quantum world as well. Although we cannot visualize quantum motion, although we don't know how we are to understand the coordinate and momentum of an electron, we do know for sure that the *mean values* of quantum quantities obey the equations of classical mechanics. This is the essence of the *principle of correspondence* which was formulated by Niels Bohr and proved in 1927 by Paul Ehrenfest.

18*

Chapter Ten

HEADS OR TAILS * TARGET SHOOTING * ELECTRON DIFFRACTION * PROBABILITY WAVES * AN ELECTRON WAVE. OF WHAT DOES IT CONSIST? * THE ATOM * PROBABILITY AND ATOMIC SPECTRA * CAUSALITY AND CHANCE, PROBABILITY AND CERTAINTY

Just imagine that on the Trans-Siberian Express, somewhere between Novosibirsk and Krasnoyarsk, you become acquainted with a very interesting person. Now imagine further that a year later you accidently meet him in front of the Rossiya cinema in Moscow. No matter how glad you are to meet him again, first of all you will be surprised because you know from experience the *low probability* of such an event.

We continually employ the words "probably", "most probably", "in all probability" and "improbable" without realizing how strictly defined are the concepts corresponding to them. Such liberties are inadmissible in science because there the concept of "probability" makes sense only if we can compute it.

This is not always possible. For example, it is impossible to predict the probability of a chance meeting with a chance acquaintance at six o'clock in the evening, October 23, 1977 in front of the Main Post Office of the city of Lipetsk, although it is certain that such a probability is not equal to zero. But the actions of people are not random ones and the theory of probabi-

lity cannot be applied to them. Consequently, all textbooks use examples of the tossing of coins with enviable constancy for explaining the laws of chance.

HEADS OR TAILS

To begin with let us note that if a test has several outcomes, the total probability that at least one event will occur is equal to *unity*. Hence the statement "the event will occur with a probability of unity" means that it is certain to occur.

It also follows that the probability of any single outcome is always less than unity. In the example with a coin, each test—the toss of a coin—can have only two outcomes, the coin will fall either heads or tails up. (We have excluded the unlikely and rare case when in falling the coin remains standing on edge.) If the coin has no trick features it is logical to assume that both outcomes of a toss are *equally probable*. It follows that the probability of the outcome being "heads", for instance, equals $^1/_2$.

It is no more difficult to calculate the probability of throwing a "three" with one of a pair of dice. It will evidently equal $^1/_6$.

The number of examples can easily be multiplied by any of us but they are all very similar to one another.

In the first place, each subsequent test (the toss of a coin) does not depend on the previous ones.

In the second place, the result of each test is a *random event*, that is we don't know (or cannot take into account) all the causes that lead to one or another outcome of the test.

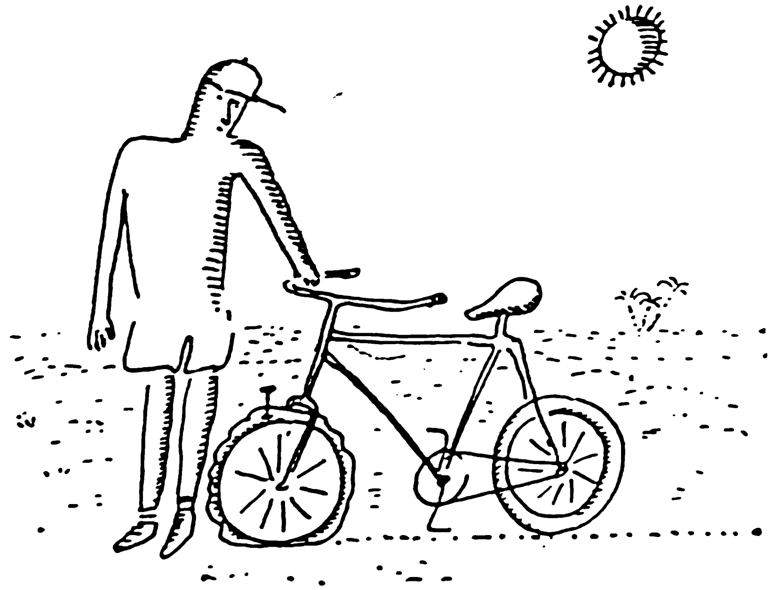
The latter is of especial importance. A coin is not an atom; its motion obeys well-known laws of classical mechanics. Using them we actually could foresee all

the details of the motion of the coin and predict how it will fall, "heads" or "tails" up. We can even plot its *trajectory of motion*. No doubt, this is all very difficult. We must take into consideration the air resistance, the exact shape of the coin, the elasticity of the floor on which it falls and many other important details. And, what is of prime importance, we must accurately specify the *initial position* and *momentum* of the coin.

It is not always possible to take into account all the conceivable factors that can influence the outcome of a test. For instance, in the case of the coin we never know its initial position and velocity with sufficient accuracy. Any, even the slightest, variation can reverse the result of the toss. Then we can no longer be sure that in *this* particular toss the coin will fall heads up. We can only say that the *probability* of the coin falling heads up in *any* toss is equal to $^1/_2$.

The simple examples we have just cited do not explain why the concept of probability is so important for quantum mechanics. Before we go any further, however, let us get acquainted, at least in general, with the principal laws of the theory of probability. The laws of chance (notwithstanding the strange combination of these two words) are just as rigorous as any other mathematical laws. They do, however, have certain unusual features and a quite definite field of application.

Although we do know, for instance, that the probability of a tossed coin falling heads up equals $^1/_2$, we cannot predict the outcome for a single toss, taken separately. All the same, we can easily check that for a large number of tosses the coin will fall heads up in approximately one half of the cases, and that the greater the number of tests, the more accurately this law will be obeyed. This is the main feature of the law of



random events. The concept of probability is applicable to any *separate* event and we can *calculate* beforehand the numerical value that corresponds to this concept. This numerical value can be *measured*, however, only when identical tests are repeated a *great number of times.*

It is very important to have identical tests, that is ones that are indistinguishable from one another. Only then can the measured value, the probability, be employed to assess each separately taken random event which is one of the possible outcomes of the test.

The unusual features of the laws of chance have a natural explanation. As a matter of fact, the tossing of a coin is a quite complicated process. We do not wish or do not know how to study it in all of its complexity. Hence, we purposely close our eyes to its complications, refuse to follow the trajectory of the coin and are interested only in the final result of the test. Such disregard for the details of the process takes its toll. Now we can *with certainty* predict only the averaged result of *numerous* identical tests, and for *each separately taken* random event we can only indicate the *probable* outcome.

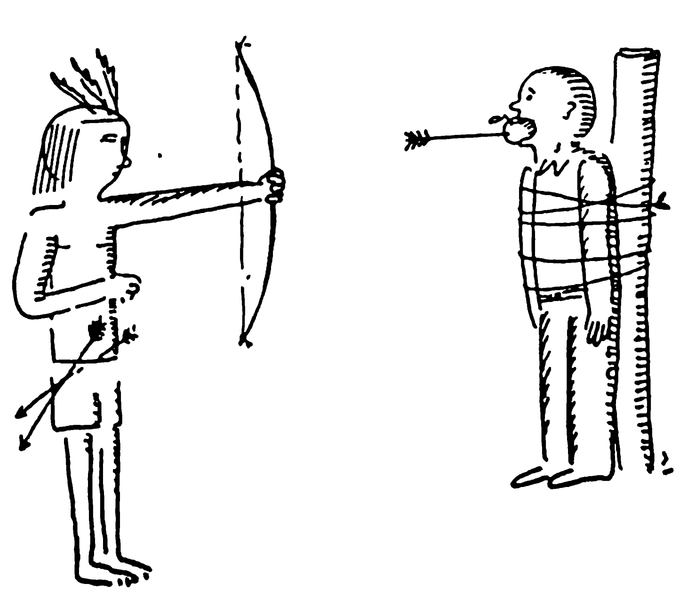
There is a widely held but nevertheless erroneous

opinion that a probabilistic description of motion is less complete than a strictly causal, classical one, with its concept of a trajectory. From the viewpoint of classical mechanics this is really so. However, if we reject a part of its rigorous requirements (for example, a knowledge of the initial coordinates and momenta), the classical description is useless. The probabilistic approach takes its place and, under the new conditions, it will be exhaustive because it will provide us with all the data concerning the system that can possibly be found out by means of experiments.

TARGET SHOOTING

In tossing a coin we deliberately do not want to know anything about the initial position and velocity of the coin. We rely wholly on chance. Our desires are somewhat different in a shooting gallery, where we always try to hit the bull's-eye. But, notwithstanding our desires (quite strong ones), we never know beforehand what part of the target each bullet will hit. Our hits are grouped into a rather regular oval which is commonly called the "ellipse of dispersion". On what does it depend?

Evidently, for all the bullets shot out of the rifle



to hit the same point of the target it will be necessary that they all have the same initial coordinate x and velocity v (or momentum p). This is possible only if you aim perfectly and if the powder charge in each cartridge is exactly the same.

Neither of these is usually achievable. Therefore, the distribution of the bullet-holes in the target always obeys the laws of chance, and we can speak only of the probability of hitting the bull's-eye or the nine-ring of the target but can never be sure of this beforehand.

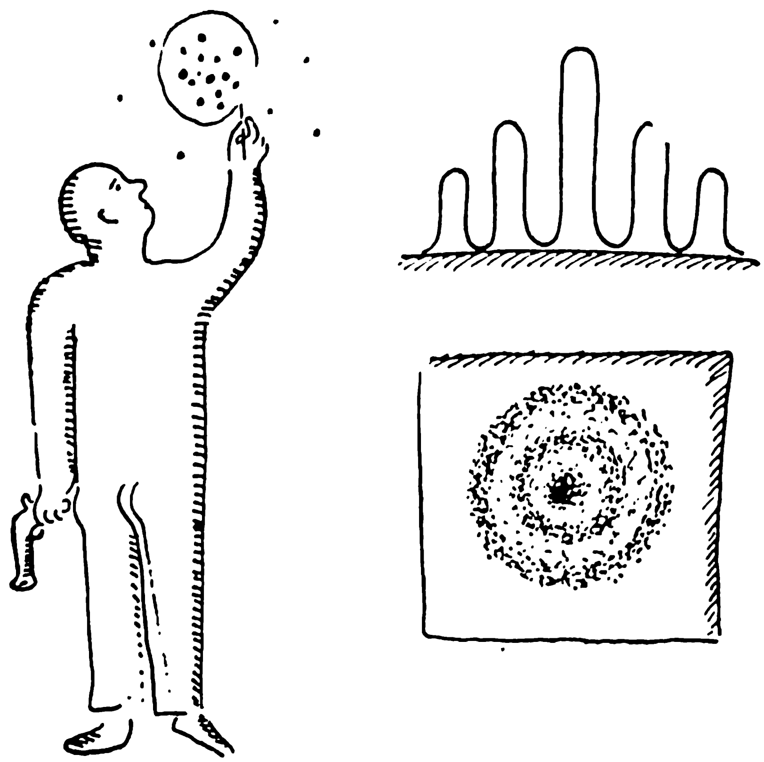
As in tossing a coin, this probability can be measured. Assume that we have made 100 shots and have hit the bull's-eye (counting ten) 40 times, the nine-ring 30 times, the eight-ring 15 times, and so on, down to zero. Then the *probability* of hitting the bull's-eye (10), nine-ring, eight-ring, etc. equals:

$$W(10) = \frac{40}{100} = 0.4; \quad W(9) = 0.3; \quad W(8) = 0.15; \text{ etc.}$$

We can even plot a diagram which, in its way, indicates the internal structure of the ellipse of dispersion.

If we now pin up another identical target and take another 100 shots, the arrangement of the bullet-holes will be entirely different from that of the first target. But the number of times we hit the bull's-eye, nine-ring, etc. will be approximately the same and, consequently, the diagram of the ellipse of dispersion will also be unchanged.

The diagram will differ, of course, for different marksmen. It will be narrower for a sharpshooter and wider for a novice. But for each separately taken marksman it will remain unchanged (at least for some time), and a skilled coach can tell which of his trainees it belongs to by just glancing at the target.



It follows from the examples given above that "laws of chance" is not a mere play on words. Each bullet taken separately will, of course, hit a random point of the target that cannot be predicted beforehand. In a large number of shots, the hits will form such a regular picture that we perceive it as being a certainty and entirely forget about the probability on which it is based.

ELECTRON DIFFRACTION

The simple example with target shooting resembles experiments in quantum mechanics much more than it seems to at first. To satisfy ourselves that this is so we shall replace the rifle by an electron gun, the target by a photographic plate and place a piece of thin metallic foil between them.

An "electron gun" is no jest but a scientific term meaning a device for obtaining a beam of electrons in almost the same way as in a TV picture tube (or a

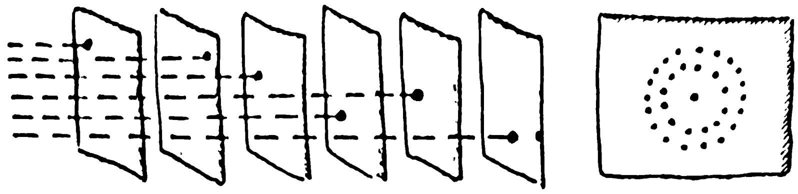
Crookes' tube). By means of diaphragms and focusing lenses we can separate a very narrow pencil of electrons from this beam. In this pencil all the electrons travel at the same velocity.

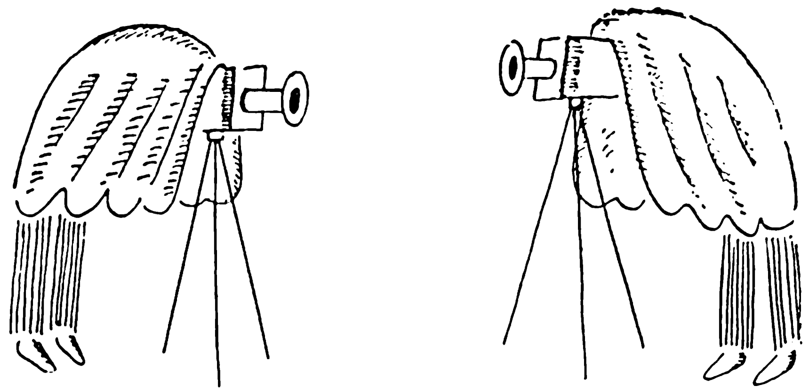
Now let us direct this pencil through the metal foil onto the photographic plate which we can then develop. What kind of picture will we find on the plate? A point? An ellipse of dispersion as in target shooting? Or an entirely different picture? We already know the answer. On the plate we shall see diffraction rings similar to those on page 282. We can now explain even the reason why they appear.

As a matter of fact we have repeatedly asserted that the electron is also a wave and not only a particle. If we haven't become accustomed to this fact so far, we should at least have remembered it. Therefore, there is nothing in electron diffraction as such that should be surprising to us. The phenomenon of diffraction always occurs when a wave passes through a substance. This is not the point. What we want to know is: a wave of *what* passes through the foil together with the electron?

Waves roll along the surface of the sea; they consist of water. Outer space is pierced by electromagnetic waves; they are oscillations of electric and magnetic fields. But *what does the wave of an electron consist of* if it itself is indivisible and has no internal structure?

Before trying to answer these questions let us conduct our experiment with the pencil of electrons in a somewhat different way. We shall release the electrons one by one (as the rifle bullets) and change the photographic plate after each electron. After developing all the plates we shall find that there is a spot on each plate. This is a trace of the incident electron. (Even if there were no other proofs, this fact alone readily convinces us that the electron is nevertheless a partic-





le.) At first glance, the black points on the plates are located entirely at random and, of course, not a single point resembles a diffraction pattern. But if we put all the plates in a stack and hold them up to the light we will find the same diffraction rings as before. It follows that the black traces of the electrons on the plates are not so randomly distributed as it seemed at first glance.

This experiment is so extremely simple that it may offend some readers by its triviality. When it was first demonstrated, however, it won over the last opponents of quantum mechanics. It is not necessary, of course, to use a separate plate for each electron. It is quite sufficient to have a single target-plate but, as before, to release the electron-bullets one by one.

As previously we cannot predict beforehand what point of the plate each successive electron will hit. This is a *chance* event. But if we release a sufficiently large number of electrons we shall obtain a *regular* diffraction pattern.

We have already run across such phenomena in tossing coins, throwing dice or in target shooting. The

evident analogy leads to the natural assumption that the process of electron scatter obeys the laws of the theory of probability. After we think this over and become acquainted with the ideas of Max Born, this guess will be replaced by certainty.

PROBABILITY WAVES

Max Born (1882-1970) taught physics in Göttingen, that famous centre of German science. He intently followed the development of atomic theory and was one of the first to put Heisenberg's quantum ideas into strict mathematical form. At the beginning of 1927 he became interested in experiments on electron diffraction.

This phenomenon in itself was no longer astonishing after de Broglie published his works. Any physicist, looking at a diffraction pattern, could explain its occurrence by means of the hypothesis on "matter waves". Moreover, using de Broglie's formula $\lambda = \frac{h}{mv}$, he could calculate the length of these "matter waves" and check whether his calculations were correct by experiment. As before, however, no one could explain what he meant by the words "matter waves". Was it the pulsation of electron-spheres? The vibration of some kind of ether? Or was it the oscillation of something even more hypothetical? In short, just how *material* were these "waves of matter"?

In the summer of 1927, Max Born proposed that "*matter waves*" are simply "*probability waves*" which describe the probable behaviour of a separate electron, for instance the probability of its hitting a definite point of the photographic plate.

Any new and profound idea has no logical basis although the loose analogies that led to it can almost

always be traced. Therefore, instead of trying to prove the validity of Born's idea by logic (which is impossible) we shall try to sense how natural his hypothesis was. Let us return again to the tossing of coins and recall the reasons why we were compelled to resort to the theory of probability. There are three:

complete independence of the separate tosses of the coin;

complete indistinguishability of the separate tosses;

random outcome of each separate toss which is due to the complete lack of knowledge of the initial conditions of each test, that is to the uncertainty of the initial coordinates and momentum of the coin.

All three conditions are complied with in atomic phenomena and, in particular, in the experiments on electron diffraction. Indeed, we know that:

electrons are nevertheless *particles* and therefore each one is scattered independently of the others;

electrons are so scanty in properties (charge, mass, and spin—and nothing more) that in quantum mechanics they are indistinguishable; at the same time the separate acts of scatter are also indistinguishable,

and, finally, the initial values of the coordinates and momenta of electrons cannot be determined *even in principle*; this is forbidden by Heisenberg's uncertainty relation $\delta x \times \delta p \geqslant \frac{1}{2}h$.

Under such conditions it is meaningless to seek the trajectory of each electron. Instead, we must learn to calculate the probability $\rho(x)$ that the electrons will hit a definite spot x on the photographic plate [or, as they say in physics, to calculate the distribution function $\rho(x)$].

This was very simple in tossing a coin. It is clear without any calculation that the probability of the coin falling heads up equals $^1/_2$. To find the function

$\rho(x)$ describing the distribution of electrons on the photographic plate it is necessary to solve Schrödinger's equation.

Max Born contended that the probability $\rho(x)$ of finding the electron at point x equals the square of the wave function Ψ (x). Thus

$$\rho(x) = |\Psi(x)|^2$$

Born's statement can be easily checked. Let us divide the diffraction pattern into concentric rings and number them like the targets in the shooting gallery. We shall then count the number N_k of electron hits in each ring of radius x_k and divide these numbers by the total number N of electrons that hit the plate. Here, as in the case of target shooting we shall obtain a set of numbers $\rho(x_k) = \frac{N_k}{N}$ which are equal to the probability of finding the electron at a distance of x_k from the centre of the target. Now it is not difficult to plot the distribution of electrons on the plate and to trace how their quantity varies with the distance from the centre of the diffraction pattern.

The curve of function $\rho(x)$ looks more complicated than the diagram of the ellipse of dispersion in target shooting. But, although we are incapable of predicting the shape of the ellipse, we can calculate the function $\rho(x)$ beforehand. Its shape is uniquely determined by the laws of quantum mechanics. Notwithstanding their unusualness, these laws nevertheless exist, which is something we cannot affirm with certainty about the laws of human behaviour upon which the ellipse of dispersion depends.

AN ELECTRON WAVE. OF WHAT DOES IT CONSIST?

When we stand on the seashore we haven't even the shade of a doubt that it is *waves* and not something else that run up the beach. Nor are we surprised by the reliable fact that all waves consist of a vast number of *particles*, or molecules.

Probability waves are just as real as sea waves. We should not be confused by the fact that these waves are made up of a large number of separate, independent, and random *events*.

Inherent in a sea wave are the properties of both a wave and a particle simultaneously. This seems entirely natural to us, and if we are surprised to find the same properties in probability, our bewilderment is, to say the least, hardly logical.

When the wind blows at sea, regular rows of waves are formed of a random accumulation of molecules. In exactly the same way, when we scatter a pencil of electrons, the separate random events—the tracks of the electrons—are regularly grouped into a united probability wave.

To satisfy oneself that sea waves are real, you do not necessarily have to be shipwrecked, although it is desirable to have at least one look at the sea. Complex instruments and special experiments are required to detect probability waves. These experiments are more complicated, of course, than a simple glance at the horizon from a seaside cliff, but this is hardly grounds for denying the very existence of probability waves.

Turning page after page of voluminous textbooks on hydrodynamics you can satisfy yourself that the paths of molecules making up a sea wave have no resemblance to wave motion. The molecules move along

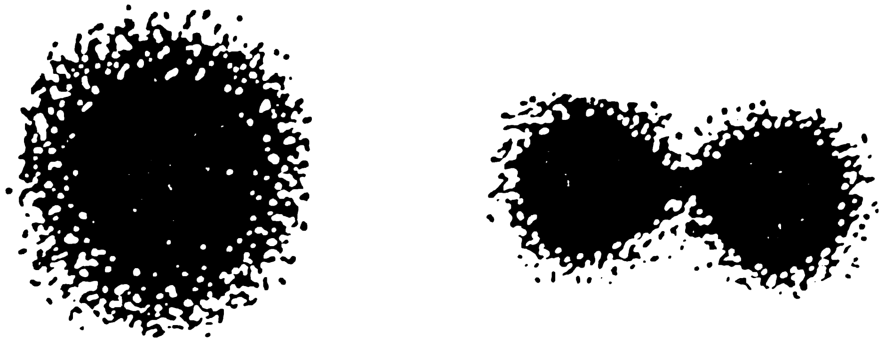
circles and ellipses, up and down, but do not participate at all in the forward movement of the waves. They *constitute* the wave but do not follow its motion. *The form of this wave is determined by the laws of hydrodynamics.*

In exactly the same way, the motion of the various electrons in the atom does not at all resemble the vibrations we likened it to previously. But as a whole the unobservable paths of the electrons belong to a united observable assembly, the probability wave. *The shape of this wave is governed by the laws of quantum mechanics.*

Analogies of this kind can be continued, but it is more important at present to clear up another point. How are we now to understand the words "the electron is a wave"? If this is not a material wave but one of probability, it cannot even be detected in experiments conducted with a separate electron.

Sometimes the wave nature of quantum-mechanics phenomena is interpreted as being the result of a certain mystic interaction of a large number of particles with one another. The reason given is that the conformity of atomic phenomena to wave laws cannot be detected at all in experiments on a single separate atomic particle. The error in such reasoning is due to an elementary misunderstanding of the laws of probability. The wave function $\Psi(x)$ and probability distribution $\rho(x)$ can be *computed* for a *separate particle*. But the distribution $\rho(x)$ can be *measured* only by the same type of tests repeated a *great number of times* on identical particles.

Nevertheless, *probability is a characteristic of a separately taken event*. Therefore, *each* electron possesses wave properties but they can be detected only in a beam of electrons. (In exactly the same way, the probability of $1/2$ that a tossed coin will fall heads



1s6 n=1 ℓ=0 m=0 2p6 n=2 ℓ=1 m=0

up is a property of each event, but this probability can be measured only in a large number of tests.)

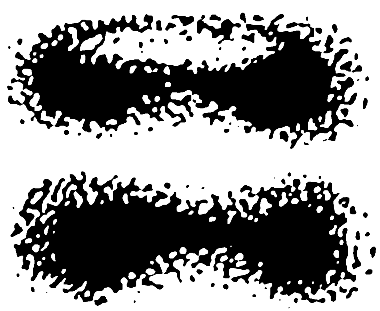
It is difficult to imagine what modern quantum mechanics could be without the concept of probability. This perhaps is the main feature that distinguishes it from classical mechanics. Of course, classical physics also resorts continually to the theory of probability, for instance, in the kinetic theory of gases. We can be comforted in this case by the hope of doing without the theory of probability if we learn to simultaneously solve a great many equations on the motions of the molecules of the gas. Quantum mechanics offers no such hopes; its equations enable, *in principle*, only the probability of events to be computed. All the same, this description will be as complete for *atomic* phenomena as the description of classical motion by means of the trajectory concept is exhaustive.

All the preceding examples and reasoning should help us to understand what the electron is outside the atom and why this *particle* is also endowed with wave properties. How can these properties—of a wave and of a particle—be combined within the atom without logical contradictions?

THE ATOM

As you may have noted, we have not tried to determine the shape of an atom directly by experiments.

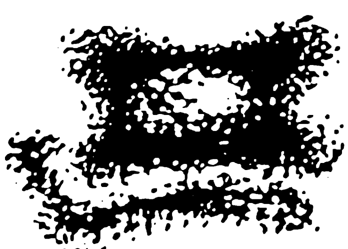
$3d\pi$ $n=3$ $l=2$ $m=1$ $3d\sigma$ $n=3$ $l=2$ $m=0$

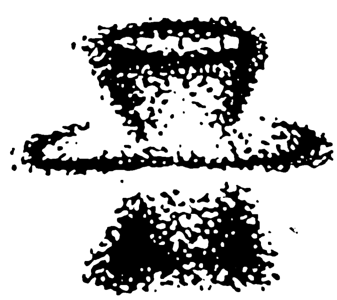


We *computed* it from Schrödinger's wave equations. We trusted this depiction because the same equation enabled us to correctly predict the finest features of atomic spectra that we can observe. Now this shape of atoms has been generally recognized and in the preceding chapter we even constructed several such shapes.

However, if we are to regard these figures as an absolute resemblance, it will be necessary to imagine the electron as being a certain charged cloud whose shape depends upon the degree of excitation of the atom. For many reasons such a picture is unsatisfactory.

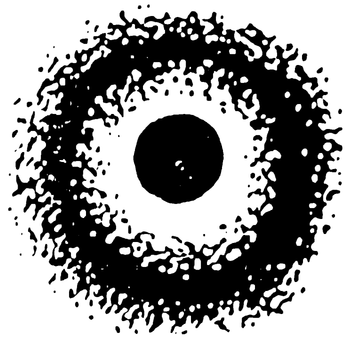
Primarily, the electron is nevertheless a particle. Of this we are certain after observing its tracks in a Wilson cloud chamber. Moreover, we are now quite certain that there are no real vibrations and material waves in the atom. Only the probability waves are real. How does this new knowledge change our previous ideas of the atom?





$4f\delta$ $n=4$ $l=3$ $m=2$ $4f\pi$ $n=4$ $l=3$ $m=1$

4f6 n=4 l=3 m=0 2S6 n=2 l=0 m=0



Let us conduct a thought experiment to determine the shape of an atom of hydrogen. We shall employ, as before, an electron gun, but now we shall aim it at a separately taken atom of hydrogen instead of at metal foil. What should we see as a result?

The majority of electrons will pass through the hydrogen atom like a shell through a wispy cloud without being deviated. But, sooner or later, one of them will collide with the electron of the atom, tear it out and be deflected itself from its initial path. Behind the atom we will now find two electrons instead of one—one from the gun and the other from the atom. Assume that we have measured their paths so accurately that we can now reconstruct their point of collision in the atom. Can we, on this basis, assert that the electron in the atom of hydrogen was located exactly at this point?

No, we cannot. We cannot even check our assumption since the atom of hydrogen no longer exists; our measurements have destroyed it.

This can easily be remedied, however. All atoms of hydrogen are indistinguishable from one another, and to repeat our experiment we can take any one of them. The second experiment will disappoint us since we shall never find the electron in the atom where we expected we would on the basis of the first experiment.

The third, fifth, or tenth experiment will only sustain our certainty that the electron has no definite position within the atom. Each time we shall find it at a new place. But if we take very many atoms and make very many measurements, noting with a point the location of the electron in the atom in each experiment, we shall finally discover, to our surprise, that the points are not scattered at random. They are grouped into the familiar figures that we have previously computed from the Schrödinger equation.

We already know how to explain this fact from the experiments on the diffraction of electrons. Indeed, we did not know at the time what point on the photographic plate the electron would hit; now we don't know where in the atom we shall find the electron. As before, we can only indicate the *probability* of finding the electron at some definite place within the atom.

At one point within the atom this probability is higher, at another it is lower, but as a whole the probability distribution forms a regular silhouette that we accept as the shape of the atom.

We have no other alternative. One can of course raise the objection that this is not a separate atom but a certain generalized image of many atoms. This is but a poor argument, since all atoms in the same quantum state are indistinguishable from one another. Hence the punctuate pictures obtained in experiments on the scattering of electrons by *many*, but *identical*, atoms determine the shape of both the generalized atom and a *single* atom taken separately.

Here, as in all phenomena governed by the laws of chance, the special features of these laws should be taken into account. For each separate atom the function $\rho(x)$ is but the distribution of the probability of finding the electron at point x of the atom. It is precisely in this sense that we can speak of the "probable

shape of a separate atom". But the picture is authentic since it is absolutely unique for any totality of identical atoms.

This up-to-date picture of the atom is infinitely distant from the concept of Democritus. Essentially, almost nothing has remained of his ideas. A fruitful error, however, is always better than barren infallibility. But for such an error Columbus would not have discovered America.

At this point we have reached the boundary accessible to those who try to penetrate deep into the atom without the aid of formulas and equations. Nevertheless, the *image* we have formed for ourselves is accurate in all its details. Without resorting to the "mathematical kitchen" of quantum mechanics we cannot *predict* a single atomic phenomenon, but we should be capable of *explaining* certain facts if we employ the new image of the atom competently and bear its origin in mind.

PROBABILITY AND ATOMIC SPECTRA

Not only its shape, but all the processes occurring in the atom obey the laws of the theory of probability. When we deal with a separate atom we can never be certain where its electron is, where it will be in the next instant, and what will happen to the atom as a result.

The equations of quantum mechanics, however, can always be used to compute the probability of all these processes. Probability predictions can then be checked, and will be found to be reliable if a sufficient number of identical tests are conducted. It took much time even for physicists like Rutherford to understand this feature of atomic processes.

He was the first to read Bohr's article on the structure of the atom before it was published. When he

had read it, Rutherford, in his customary straightforward and brusque manner, asked Bohr how an electron on the n-th orbit knows where to jump, to the k-th or the j-th orbit. Then, in 1913, Bohr could not answer Rutherford. Now, when three generations of physicists have worked on atomic theory, the problem has been cleared up sufficiently so that even we are capable of understanding the ABC's of it.

An electron "knows nothing" beforehand; it only obeys the laws of quantum mechanics. According to these laws, there is always a strictly definite probability that an electron in any quantum state (for instance, one with the quantum number n) will go over to any other state (for instance, the state k). As always, the probability W_{nk} of the transition $n \rightarrow k$ is a *number* whose value depends upon the selection of the pair of quantum states n and k. If we consider all the possible combinations of n and k we shall obtain a square table of numbers W_{nk}. We already know that such a table is called a *matrix*. And this matrix *represents* the internal state of the atom.

Only now can we appreciate the intuition of Heisenberg who correctly sensed the specific features of the quantum processes in the atom and introduced his matrices $\{X_{nk}\}$ and $\{P_{nk}\}$ even though he knew nothing of the laws of probability governing these processes. Somewhat later it was found that in terms of these matrices the probability matrix W_{nk} can be quite simply expressed, and that Heisenberg's matrices, in their turn, can be easily calculated by solving Schrödinger's equation.

Although it is simple, the reasoning we have just followed through is exceptionally fruitful. With its aid, for example, we can quite readily explain why in the yellow doublet of the sodium D line the intensity of the D_2 line is twice that of the D_1 line.

Even finer features of the structure of these lines, for instance, the law of intensity variation within the lines themselves, can be cleared up by systematically employing the equations of quantum mechanics. But all these pleasures are available only to specialists.

CAUSALITY AND CHANCE, PROBABILITY AND CERTAINTY

The probability interpretation of quantum mechanics was not to the liking of many physicists and gave rise to numerous attempts to return to the previous classical scheme of describing atomic phenomena. This tendency to make use of old knowledge under new conditions at any cost is understandable but in no way justifiable. One is reminded of the old Prussian soldier who returns home, at the turn of the century, after years of service and tries to interpret all the diversity of civilian life from the viewpoint of the military drill regulations. He will be undoubtedly outraged at the disorder he finds in the local dance pavilion, and it will be difficult to make him understand that the rules on a dance floor are quite different from those of the army drill ground.

Not so long ago, not too honest interpreters of quantum mechanics attempted, with suspicious zeal, to annul it on the grounds that it could not be accommodated within the scope of schemes that they had worked out. They were indignant with the "free will" that has allegedly been imparted to the electron, made fun of the uncertainty relation and seriously contended that quantum mechanics is a useless science since it deals only with the probabilities of events and not the real events themselves. Those who have attentively followed our previous arguments can understand the absolute nonsense of such charges. But even those who

treat the theory of the atom with due respect do not always realize how they are to understand the causality of atomic phenomena if each one of them occurs by chance, and how reliable the predictions of quantum mechanics can be if they are based on the concept of probability.

The everyday notion of causality—"each phenomenon has its own cause"—requires no explanation but is useless to science. Causality in science requires a rigorous *law* by means of which it is possible to follow the sequence of events in time. In the language of formulas such a law has the form of a differential equation which is called an equation of motion. In classical mechanics such equations—Newton's equations of motion—enable the *trajectory* of a particle's motion to be predicted.

Such a scheme of the explanation and prediction of the phenomena of nature as we have roughly outlined here has always been accepted as the ideal causal description in classical physics. It leaves no room for doubt or misunderstanding. To underline this quality, physicists later called the causality of classical physics *determinism*.

There is no *such* causality in atomic physics. Instead, it has its own, quantum-mechanical, causality and its law, the Schrödinger equation. This last is even more powerful than Newton's equations since it detects and singles regularity out of a chaos of random atomic events. In a sense it resembles a kaleidoscope in which a random combination of bits of coloured glass produces a pattern which has both meaning and beauty.

The combinations of words "statistic causality" and "probability regularity" grate on the unpractised ear because of their incompatibility. ("Soapy soap", as the jocular phrase has it, sounds bad enough, but "un-

soapy soap" is just too much.) The words really are incompatible but in atomic physics we are compelled to employ them together to fully explain the special features of quantum phenomena. Actually, there is no logical paradox in these phrases. The concepts of "chance" and "regularity" are complementary ones. According to Bohr's complementarity principle both are required, equally and simultaneously, in order to define a new concept "quantum-mechanical causality" which is something more than the simple sum of the concepts "regularity" and "chance". In exactly the same manner, an "atomic object" is always something more complex than the artless sum of "wave" and "particle" properties.

In spite of their logical perfection it is hard to get used to such constructions and to acknowledge that they are natural. As usual in quantum physics the logical difficulties are due to specific features of our language and upbringing. The concepts of "regularity" and "chance", "certainty" and "probability" were formed long before the founding of quantum mechanics, and the meaning usually given to them does not depend upon the wishes of quantum physicists.

Essentially, the problem of probability is always one of observation; we determine what will happen if we do this or that. In classical physics two identical tests under identical initial conditions should always lead to the same final result. This is the essence of classical causality, or determinism. The peculiarity of quantum-mechanical causality is that even under invariable conditions it can indicate only the *probability* of the outcome of a single test. But, in return, it can with absolute *certainty* predict the distribution of outcomes for a great number of the same tests.

We can endlessly juggle the paradoxes "regular chance" and "certain probability" but this will add

nothing to our knowledge of the atom. This is not the point. We must simply understand, if only once, that the probability description of the atom is not the result of averaging as yet unknown atomic models (as in the case with the tossing of a coin). Here we have reached the limits of the capacity of present-day science. As long as Heisenberg's uncertainty relation remains valid, we cannot *in principle* refine upon our data on atomic systems. Actually, we have no need to do so. All bodies in nature consist of a vast number of atoms, and quantum mechanics predicts the properties of such systems uniquely and with no arbitrariness whatsoever.

The concept of probability completed the logical scheme of quantum mechanics. It was indispensable for a logically consistent accomplishment of the higher synthesis of the complementary pairs of concepts: wave and particle, continuity and discreteness, causality and chance, and phenomenon and observation. Only after this was it possible to finally establish that all these concepts form an indivisible system and that each one depends upon the context of the others. The form of the answers that quantum mechanics gives to our questions depends on which aspect of an atomic phenomenon we wish to study more intently than its complementary aspect.

In our study of nature we always, consciously or unconsciously, divide it into two parts, the system plus the observer. This division is not unique and depends upon *what* phenomenon we are investigating and what we *want* to find out about it.

If by the word *phenomenon* we have in mind the motion of a single *particle*, then such an event is *discrete*, *random* and for the most part unobservable. But if by the word phenomenon we mean the results of observation of the motion of a great number of iden-

tical atomic objects, then this event is *continuous*, regular, and is described by the *wave* function.

Quantum mechanics deals only with the second kind of events. For them it can make reliable and unambiguous predictions that have not been disproved so far by even a single experiment.

ROUND AND ABOUT THE QUANTUM

PEOPLE, EVENTS, QUANTA

The results of science are independent of the psychology and wishes of individual persons; in this objectivity lies the power and value of science. Nevertheless, it is a human affair and that is why its history is also the history of human destinies and not only the development of physical concepts and mathematical methods. Alongside their discoveries any detail in the lives of scientists seems significant. We continually wonder how some trifle, one of those that make up the lives of even the greatest of men, affected the work that made them immortal.

The history of the founding of quantum mechanics has preserved for us certain lively reminiscences that help to picture the environment of tension and enthusiasm in which people of various nationalities, ages and dispositions created modern quantum mechanics in only three years.

Everything began perhaps on the day when Sommerfeld entered the classroom where sophomore Heisenberg was busy studying and gave him a photographic plate with some spectral lines suggesting that he try to find some regularity in their arrangement. Or, maybe, it all began at the end of May in 1925, when postgraduate Heisenberg got hay fever and Max Born,

his instructor at that time, proposed that he take a holiday on the island of Heligoland in the North Sea. There he carried out his famous calculations and experienced a rare emotional enthusiasm of which he later related: "Finally the evening came when I could begin calculating the energy of the various terms in the energy table or, as they say today, the energy matrix. The excitement that gripped me ... prevented me from concentrating, and I began to make mistake after mistake in the calculations. I could reach the final result only at three o'clock in the morning. At first I was frightened ... . The thought that I had become the holder of all these treasures—the elegant mathematical structures that nature had revealed to me—took my breath away. I could not sleep. It began to grow light. I left the house and walked toward the southern end of the island where a lone rock jutted out above the sea ... . Without much trouble I climbed the rock and awaited sunrise on its summit."

By June 5, only three weeks later, when he returned from his holiday, he wrote to Krönig about his calculations. On June 24, he sent a detailed letter to Pauli which contained the basis of the future matrix mechanics. True, Heisenberg's mathematical training was not on a level with the profoundness of his physical ideas. He did not even know that the quantities he was introducing had long been known in mathematics by the name of matrices. For this reason, Heisenberg's theory could be rigorously formulated mathematically only with the aid of Max Born and the then still very young Ernst Pascual Jordan. By July, in Göttingen they had put the last touches to the new matrix mechanics.

The same problem was solved independently of them in Cambridge by Paul Dirac who, at a seminar supervised by Pyotr Leonidovich Kapitsa, heard the

report made by Heisenberg on his visit to England in the summer of 1925, soon after he got well.

In the fall of the same year, Wolfgang Pauli used the new mathematics to determine the energy levels in an atom of hydrogen, showing that they coincide with the levels of Bohr's atom.

In the same summer, Goudsmit and Uhlenbeck proposed the hypothesis of electron spin, Louis de Broglie finally worked out his idea on the waves of matter, and Walter Elsasser and Albert Einstein proposed that these theories be used to explain the experiments of Davisson and his assistants on the reflection of electron beams from the surface of metals.

The origin of wave mechanics goes back to 1923 with the doctoral dissertation of de Broglie. Paul Langevin, to whom it was presented, did not particularly support the idea it set forth, but sent it on to Einstein to be reviewed. Einstein, in his turn, earnestly advised Max Born, "Read it! Although it seems to have been written by a madman, it has been written soundly". Moreover, he cited it with sympathy in his subsequent works, and Schrödinger was afterwards grateful to Einstein that he so opportunely "gave him a flick on the nose by pointing out the importance of de Broglie's ideas".

Schrödinger's wave mechanics was born during the Easter holidays of 1926. Unfortunately, Schrödinger left no lively memories, as Heisenberg did, of this *Sturm und Drang* period of quantum mechanics. Perhaps the reason is that he made his most important discoveries in his mature years, when the ardour of youth for eager action is already dissolved in the clear wisdom of knowledge, and when the immediate joy of discovery is subdued by the understanding of the relative value of all that exists.

Theoretical physicists met wave mechanics with

distrust because it obviously lacked quantum jumps, to which they had become accustomed only recently and with such difficulty, and which were now considered the principal features of atomic phenomena.

In June 1926, Heisenberg went to Munich to visit his parents and "... gave way to absolute despair" after hearing the report of Erwin Schrödinger and his interpretation of quantum mechanics at one of the seminars.

On the other hand, experimental physicists (Wilhelm Wien and others), who called Heisenberg's theory "atomystics" (i.e. mystics of the atom), greeted Schrödinger's theory with enthusiasm.

Arguments on wave mechanics continued for hours and days and reached a climax in September 1926 when Schrödinger came to Copenhagen at the invitation of Bohr.

Schrödinger was so tired of the endless discussions that he fell ill and spent several days in Bohr's home. Almost all the time his guest was ill Bohr spent at his bedside.

From time to time, raising his finger with a characteristic gesture, Niels Bohr would repeat, "But Schrödinger, you must nevertheless agree... ."

"If we are going to stick to this damned quantum-jumping, then I regret that I ever had anything to do with quantum theory," Schrödinger once exclaimed almost in complete despair.

"But the rest of us are thankful that you did," Bohr replied, "because you have contributed so much to the clarification of the quantum theory."

As time went by, the standpoints of the advocates of matrix and wave mechanics drew nearer to each other. Schrödinger himself proved their mathematical equality and Max Born conjectured in the summer of

1926 what physical meaning should be ascribed to Schrödinger's Ψ-function.

Experiments on the diffraction of electrons which became known in the autumn of 1926 greatly strengthened the belief in the theories of de Broglie and Schrödinger. Physicists gradually came to understand that the "wave-particle" duality is an experimental fact that should be accepted without discussion and employed as the basis for all theoretical constructions.

Now scientists tried to comprehend to what consequences this fact leads and what restrictions it imposes on their conceptions of atomic processes. Here they ran into dozens of paradoxes, whose meanings they often could not understand.

That autumn in 1926, Heisenberg lived in the garret of the Physical Institute in Copenhagen. In the evenings Bohr would climb the stairs to his room and their discussions would frequently last till after midnight. "Sometimes they would end in complete dispair, owing to the incomprehensibility of quantum theory, in Bohr's apartment drinking a glass of port," Heisenberg recalled. "Once, after such a discussion, I went downstairs and outside to take a walk in the fresh air of the park behind the Institute and to calm down before going to bed. During this walk under the night sky studded with stars an idea flashed through my mind. Ought we not to postulate that nature permits the existence of only such experimental situations in which ... it is impossible to determine the position and velocity of a particle simultaneously?"

This idea was the germ of the future uncertainty relation.

It was perhaps to reduce the tension of these days that Niels Bohr went to Norway in February 1927 to take a rest and do some skiing. Left to himself, Heisenberg continued to think intently on all these

matters. He was preoccupied, in particular, with a question put long ago by his class-mate, the son of the well-known physicist Drude: "Why can't the orbit of an electron in an atom be observed by means of rays with a very short wavelength, for instance, gamma rays?"

A discussion of such an experiment soon led him to the uncertainty relation and on February 23 he wrote Pauli a 14-page letter about it.

A few days later Bohr returned from his holiday with the idea for the complementarity principle which he had finally thought out in Norway.

After several more weeks of intense discussions with the participation of Oskar Klein everybody came to the conclusion that the uncertainty relation was a special case of the complementarity principle and one that could be expressed in the language of formulas.

In the subsequent months the interpretation of the mathematical formalism of quantum mechanics was supplemented, refined, and finally approved at the Solvay conference in Brussels in the autumn of 1927. This conference was attended by Planck, Einstein, Lorentz, Bohr, de Broglie, Born, Schrödinger and, of the younger physicists, Heisenberg, Pauli, Dirac and Kramers. This turned out to be the severest test of the principles of quantum mechanics. This new branch of physics passed the test with flying colours and has not undergone any changes since that time.

The founding of the science of the atom was not the only achievement of Bohr's institute in Copenhagen during those years. An international family of young physicists was formed there. Among them were H. Kramers, P. Ehrenfest and L. Rosenfeld of the Netherlands, O. Klein of Sweden, P. Dirac of England, W. Heisenberg of Germany, L. Brillouin of France,

W. Pauli of Austria, and G. Gamow and L. Landau of the USSR.

This alliance of scientists, unprecedented in the history of science, was distinguished for its uncompromising striving for the truth, sincere zest for the grandeur of the problems they were to solve and an ineradicable sense of humour which harmonized so well with the general spirit of intellectual chivalry. "There are things so serious that they can be spoken of only jokingly," was a favourite saying of Niels Bohr, who became their teacher and father confessor.

They all had the spark of cosmic feeling which is related, in a sense, to religiosity, and distinguishes great men from ordinary people. They preserved this feeling of eternity through all the civil disturbances whose contemporaries and participants they were to become.

Many years later, political storms would scatter them all over the world: Heisenberg would become the head of the German "Uranium Project", Niels Bohr would escape from the Nazis and go to Los Alamos to work in the American centre for atomic investigations, Goudsmit would become the head of the Alsos Mission whose purpose was to find out what Heisenberg had been able to do in the building of the German atom bomb.

Very few of these people are now alive and the whole epoch in physics, comparable only with those of Galileo and Newton, follows in the wake of those who have already gone.

Chapter Eleven

WHAT IS QUANTUM MECHANICS? * WHAT IS AN ATOM? * PHYSICAL REALITY

Nicholas Murray Butler, president of Columbia University for almost half a century, once said: "An expert is one who knows more and more about less and less." Someone, probably a good newspaperman, embellished this witticism to one that Niels Bohr liked to repeat when explaining his principle of complementarity by examples. He would say: "A good expert is one who knows a lot about a little; a good newspaperman is one who knows a little about a lot. At the limit, the best expert knows everything about nothing, and the best newspaperman, nothing about everything."

Kozma Prutkov (the collective pen-name of three Russian writers of the eighteen-fifties, famous for their aphorisms) knew nothing whatsoever about the principle of complementarity and expressed his thoughts in much simpler language. He said: "An expert is like a cheek swollen from a tooth-ache; his knowledge is one-sided." Or the opposite: "You cannot bind the boundless."

These puns and jests have acquired a special meaning in our times when we are daily subjected to a ne-

ver-ending stream of information through books, radio, TV and journals (the world's libraries already contain over 60 million books, and each minute a new book is published). When untrained people suddenly find themselves in this heavy stream of knowledge, they lose hope of understanding anything at all and just prefer to float down with the stream, knowing nothing about anything. None too clever persons try to deceive themselves and others by dipping up some of the froth of this knowledge at the top of the stream. The more so because this froth is now so available and is exquisitely packaged.

But the great majority of people strive, nevertheless, to single out of the stream of information only the knowledge that is absolutely necessary for their needs or that affords them unaccountable pleasure, each in his own way of course, and to the extent nature has allotted him. This process is strictly individual, spontaneous to a great degree, and does not lend itself to irreproachable logical analysis. You cannot put a re-

cipe in the cradle of a newborn babe indicating when, in what order, and which books it is necessary for him to read all through his life.

Certain rules, however, do exist, just as methods are known for prolonging one's life even though there never have been, nor can be, any recipes for immortality. It is impossible to know everything. It is good to know a lot. But there should be something that one knows thoroughly. Only such knowledge can give a person confidence and the capacity for independent thinking; only it can enable him to create new values.

Undiscovered yet is the "uncertainty relation" for the process of cognition, which should indicate a balance between the "quantity" and "quality" of knowledge needed by a person, and strictly determine the limits of feasibility in selecting an object of study and the method to be followed. But one thing is beyond question: superficiality yields neither benefit nor pleasure. We all may, to a more or less extent, be amazed by the logical elegance and power of science, but small talk about science bears the stamp of exceptional futility if it is not backed up by a knowledge of exact facts and clear-cut conceptions.

All during our story of quantum mechanics we have tried to employ only such—accurate and intelligible—facts and conceptions. Of course, even if you have mastered them, you cannot design a laser or a nuclear reactor. But likewise you do not attend concerts and lectures on music for the purpose of learning to play the violin.

We have come to the end of our narrative. Can we now intelligibly answer the two principal questions that were put at the very beginning?

WHAT IS QUANTUM MECHANICS? WHAT IS AN ATOM?

It appears that answers do exist to these questions although they may seem somewhat peculiar.

We began our story of quantum mechanics with the definition: "Quantum mechanics is the science of the structure and properties of atomic objects and phenomena." We abandoned it at once because it is obviously useless until we can define the concept of the "atomic object" itself. Instead, we resorted to an analysis of experiments in which the properties of an atom are displayed and to an analysis of formulas which enable the results of these experiments to be predicted.

We have gradually revealed an amazing fact. All the formulas that describe properties of atomic objects necessarily contain Planck's constant h. And now when a physicist sees an equation containing the quantum of action h, he readily reaches the infallible conclusion that he is dealing with an equation of quantum mechanics.

On this basis quantum mechanics could be defined as a system of equations in which the presence of Planck's constant h is obligatory. Such a definition, however, can only reassure our striving for unambiguity and formal strictness, but is essentially of no use. Definitions of science should concern the object being studied and not be restricted merely to the method by means of which this study is accomplished.

After our numerous attempts to answer questions on the essence of the atom, we could simply say: "The atom is the sum of our present knowledge about it." But this again is not a definition. It is simply a plausible excuse to evade one.

What words can we use to define the *concept* of an "atom" concisely and unambiguously?

We have seen time and again that no single word of our speech is capable of accommodating all the diversity and complexity of this concept. Then we resorted to the equations of quantum mechanics and with the aid of *formulas*, bypassing words and rigorous definitions, we have constructed an *image* of the atom for ourselves. Here we intentionally followed the method employed by modern physics.

What is the essence of this method? First of all, it forbids one to speak of phenomena by themselves, independently of the method by which they are observed. The concepts of a "phenomenon" and its "observation" exist independently only in our mind, and even then only with restricted accuracy. For a physicist these concepts are two aspects of the same physical reality which he studies and in whose objective existence he certainly believes.

The concepts of "phenomena" and "observation" are complementary in Bohr's sense of the word. They are incompatible because observation destroys the primary phenomenon. But they are equally necessary; without observation we know nothing at all about a phenomenon. Their complex unity and interaction do not allow us to comprehend the essence of a phenomenon by itself, but they help us to reveal the *relations* between phenomena.

We can write these relations down by means of formulas or tell about them in words. But the words alone will remain empty unless the formulas are written down alongside them. And the formulas are stillborn until we find a way to explain what they actually mean. To completely explain the combination "phenomenon-observation" we require a harmonic concord of concepts and formulas. Only then can we form a satisfactory image of a physical phenomenon for ourselves.

At this stage the chain of cognition of the new physics

$$\text{phenomenon} \qquad \text{image} \leftarrow \text{concept} \leftarrow \text{formula} \leftarrow \text{experiment}$$

is modified once again. It becomes more complicated and acquires the following form:

$$\left\{\begin{array}{c}\text{phenomenon}\\ \downarrow \quad \uparrow\\ \text{observation}\end{array}\right\} \rightarrow \left\{\begin{array}{c}\text{concept}\\ \downarrow \quad \uparrow\\ \text{formula}\end{array}\right\} \rightarrow \text{image}$$

During all our attempts to define the concept of an "atom" we were unconsciously approaching this scheme.

Present-day physicists begin their training with formulas. This is probably very reasonable. In studying a foreign language it is better to learn to speak it from the very beginning without bothering to clear up why a word is written the way it is and not some other way.

Following the formulas, the physics students master words which are necessary to pronounce and without which no contact between people is possible at all. Formulas, however, do not have precise verbal equivalents. The teaching of modern physics therefore consists in expounding uncustomary things with customary words, but each time from a slightly different viewpoint. The aim here is to submerge the new concepts from the sphere of the logical and conscious into sphere of the intuitive and subconscious. This is a vital condition for any creative work.

This method of teaching physicists imperceptibly deforms the system of their images, concepts and even their system of associations. Physicists are jarred by the immaculately correct verbal structures of most popular-science books, just as anyone is who knows his language well. In such books they infallibly dis-

tinguish an almost imperceptible foreign accent. It is frequently impossible to convey the meaning of a foreign phrase without destroying its initial structure. The language used by physicists is often Russian, English or some other only by name and some of the words used. Actually, it is a specific language whose vocabulary and grammatical constructions drive editors to despair. But in each attempt to "polish" an ungainly physical phrase according to the standards of literary language it loses something, like foreign poetry does even in the best of translations.

The unpolished physical truth is that

an atomic object is a physical reality the properties of which can be described by means of the equations of quantum mechanics;

quantum mechanics is a system of formulas, concepts, and images that enable the observed properties of atomic objects to be pictured, explained, and predicted.

When these two definitions are placed side by side they seem to mock common sense. They are nevertheless natural within the scope of the complementarity principle. The point is that the concepts of an "atom" and "quantum mechanics" are complementary in Bohr's sense of the word. So also are the concepts of a "coordinate" and "momentum", a "wave" and a "particle", a "phenomenon" and "observation", "probability" and "certainty", and "causality" and "chance". They cannot substitute for each other, and not one of them can be defined exhaustively without taking the other, complementary concept, into account. This is something we must get used to; it is the destiny of all profound concepts.

Niels Bohr never tired of repeating this to the end of his days. He even proposed a method for distinguishing a profound statement from a trivial one: you must construct the opposite statement and if it turns out

to be absurd, the initial statement was trivial. To illustrate this he gave the following examples. The assertion that "God exists" is a profound one because the opposite one "there is no God" is just as profound. The statement that "all people are mortal" is a trivial one because the opposite statement that "all people are immortal" is absurd.

Just as any other capacity given us by nature in only a rudimentary form, we should develop in ourselves the ability to think in accordance with Bohr's complementarity principle. This cannot be done by simply mastering the formal rules for constructing concepts. We must also have an idea of where they were evolved. This is why we have taken so much time to thoroughly examine the experiments out of which the concept of an "atomic object" was subsequently crystallized. By itself, apart from the experiments, the concept has no real meaning. It simply consolidates, in the language of formal logic, the intuitive image that was gradually formed in our consciousness largely unknown to our will.

Our present definition of quantum mechanics coincides almost word for word with the one given at the very beginning of this book. If it sounds entirely different to you now, then you have not read the intervening pages in vain.

We could have finished our story about quantum mechanics at this point except for one important circumstance. The fact is that when we said that the "atom is a physical reality ..." we unintentionally touched upon an extensive boundary region between physics and philosophy.

The concept of a "physical reality" is the final one that is inevitably referred to in any serious attempt to explain something in physics. Owing to its universality, it is so vast and all-embracing that we find

it impossible to define it only by physical means. It proves necessary to resort to philosophy with its concept of objective reality.

As is known, objective reality is everything there is, or has ever been, independently of our consciousness. (Incidentally, our consciousness and sensations are also objective reality.) This definition is insufficiently concrete for science because it does not commit itself to anything except a belief in the objective nature of the knowable world. This is something that all scientists believe in anyway, otherwise they would not devote their whole lives to the cognition of this reality. Opinions differ only as to the nature of *physical reality*, its truth and its uniqueness. A great many physicists consider that

physical reality is the part of objective reality that we get to know by means of experiments and our consciousness, that is all the facts and numbers that we obtain by means of instruments, as well as all the notions we have about them.

Opinions are vacillating. Why are we sure that the picture of physical reality obtained in this manner is the truth? Or, to put it more mildly (no one really knows "what truth is"), why are we sure that this picture is the only possible one?

PHYSICAL REALITY

Defining concepts more accurately is a complicated business and not always a harmless one. In his time Socrates had to pay with his life for his persistent attempts to clear up the meanings of the principal moral and ethical conceptions: good and evil, truth and error, justice and the law.... Socrates lived in ancient Greece in its Golden Age. Like a true man of wisdom he would spend his days in the sunny squares

of Athens and would pester his fellow citizens with questions like the following:

"Tell me, O learned Hippias, what is beauty?" His scholarly companion undertook the explanation with gusto but soon found that he could not break out of the circle of examples. He could explain more or less comprehensibly what a beautiful woman is, or a beautiful vase with roses, or a beautiful horse, but he could not explain what beauty is by itself. Each time he found that this was beyond his power.

The tragedy of this typical conceptual situation has been understood down through the ages. Wise men realized it and resigned themselves.

"Truth lies beyond the limits of the consciousness and cannot therefore be expressed in words," they said in ancient India.

Expressed in the American vernacular, modern philosophers write, "If you can't say it in words, you'd better shut up."

In our endeavours to answer the question "What is an atom?" we inevitably encounter the same difficulties. Like the ancient philosophers we find it hard to overcome them with words. But we have it easier. The formulas that appeared with the development of science enable us to avoid many of the difficulties.

Various examples have gradually convinced us that an atom is neither the spectral lines it emits, nor the diversity of crystals made up of atoms, nor the heat of white-hot iron, nor the electrons that are ejected from atoms. Like Socrates' companions we are now obliged to admit that the atom is something indefinite in itself, a certain general cause of atomic phenomena which cannot be perceived independently of them.

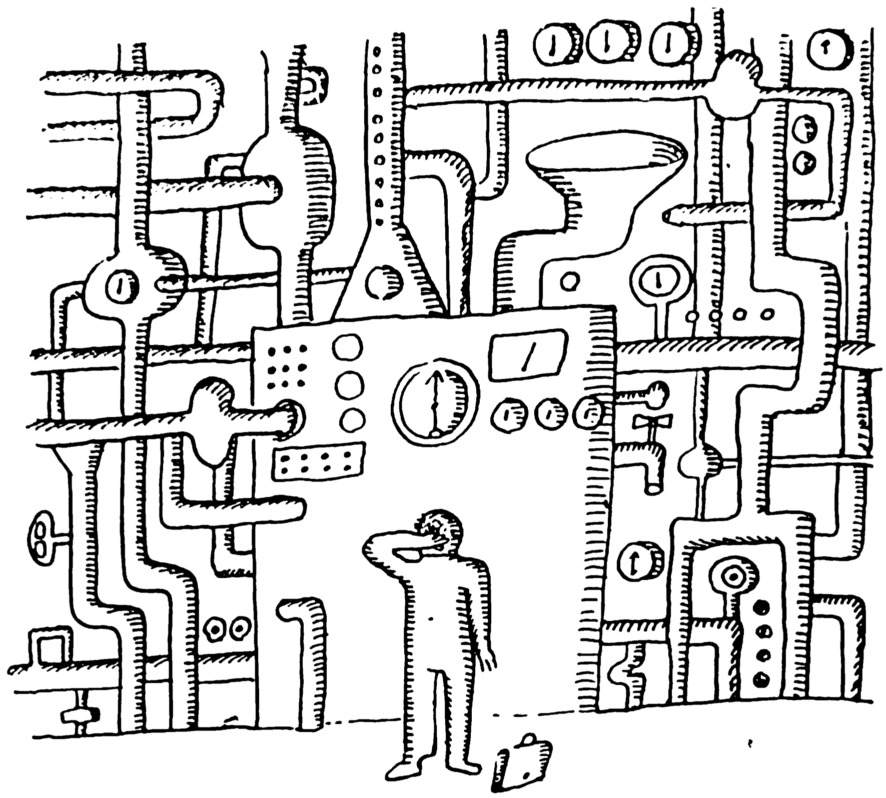
Enter any physical laboratory and make an attempt from the threshold to determine what phenomenon

of nature is being investigated there. You will see a conglomeration of instruments and a tangle of wires behind which you cannot detect the phenomenon being studied or even the physicists engaged in its investigation. When you are told in this situation that "we are studying the splitting of spectral lines in a magnetic field", these words can call forth only polite attention on your part but you can hardly be sure that you are not having your leg pulled.

Even when a photographic plate is handed to you and you see thin black lines on it, they bring up no associations with the atoms from whose depths (as the physicists will assure you) rays were emitted that were subsequently transformed by the spectroscope and left such distinct tracks on the plate.

These explanations will not seem very convincing to a person who has nothing to do with physics. It is more or less clear to him how an auto mechanic determines what is wrong with an engine by listening to its knock, or how a physician diagnoses a disease of a patient correctly on the basis of his complaints. Our layman in physics knows that it is always possible to disassemble the engine; this will not change its parts. If the worst comes to the worst a diagnosis can always be checked by a post-mortem examination. In both cases we know all the parts of which the whole is comprised. Even if you are not a watch-maker, you can understand how your watch works after you take it apart, and why the visible motions of its hands do not resemble the usually invisible motion of its springs and pinions.

Everything that concerns atoms is much more complicated. We observe the external effects of their properties, such as their spectra, the colour of bodies, their specific heat, and crystalline structure, but we cannot remove the "back of the watch case" to see



what "actually" makes the wheels go round. On the basis of an assembly of facts, concepts and formulas, we have formed a certain image of the atom for ourselves. But since no independent method exists by means of which we can check this image, a natural question arises: "Cannot we think up a different image of the atom which will lead, however, to the same observed consequences?"

This is no idle question; almost all the famous physicists have tried to decide it. Sceptical common sense will put the matter somewhat differently: "Everything you have thought up is wrong, actually everything is quite different!"

This objection is hard to refute because the concept "actually" has not actually been defined. In the everyday sense, all that "actually" exists is what we can check by means of our five senses, or that which we can verify by extensions of our five senses, i.e. instruments.

Even the last statement raised objections at first.

The contemporaries of Galileo contended that his discoveries of sun spots and the moons of Jupiter were not actually discoveries at all, but were due to errors in the telescope he used.

Let us assume that we have advanced since the times of Galileo and now believe in the truth of the readings of instruments. Then there still remains freedom for the interpretation of these readings. The question of the meaning of the concept "actually" is now changed to "How unique is the interpretation of experiments with respect to phenomena inaccessible to direct sensual perception?"

The common sense of a person having nothing to do with science should make him admit that such an interpretation is ambiguous. After a superficial visit to a physical laboratory this *a priori* conviction can only be strengthened. But only physicists know that the facts and concepts of their science permit free interpretation only in the process of their discovery and establishment. But as soon as they have been included into the general system of physical knowledge and coordinated with it, it is almost impossible to change them unless we trespass the limits of their applicability.

In extending and refining the system of scientific knowledge, we are compelled to depart farther and farther from direct sensory perceptions and from concepts based on them. Such a process of abstraction is irreversible but this should not distress us. It only shows that our intellect is capable of understanding even that which we cannot imagine.

The abstraction of scientific concepts is just as great a necessity as the invention of letter alphabets in place of ancient picture writing and hieroglyphics. Not a single letter in the word "rhinoceros" reminds us of the animal but the whole word infallibly brings the

necessary image to our minds. It is obvious to everyone that our modern culture is inconceivable without printing. But comparatively few people realize that the development of science is impossible without a further abstraction of scientific concepts. Plain common sense should resign itself to this fact and not demand explanations. Abstract science, like music, requires profound understanding and not justification. Only with its aid can we get to know the unusual atomic reality, although this reality is entirely of a different kind than that of ponderable and visible stones and trees.

But man always tries to make even this "abstract reality" *visualizable*, that is to reduce it to a small number of proven images. This striving is deeply inherent in man and, consequently, physicists have gradually developed their own queer system of images. This system almost certainly does not correspond to anything real in nature and it cannot be described in words, but it nevertheless enables physicists to find the relations between phenomena at moments when they are thinking most intensely about them.

The chains of cognition that we drew previously, from phenomena through concepts and formulas to images, are no more than schemes which give only a faint idea of the processes that occur in the mind of a scientist when he tries, in a random set of facts, to see simple relations, to define them with words and to find their place in the general picture of nature.

A single word does not constitute a language; you need a set of words and rules of grammar by means of which the words are to be arranged. A single scientific fact, however important it may seem, likewise does not mean anything by itself if we do not know its place in the general system of knowledge. It ac-

quires a meaning and significance only together with its interpretation.

Recall the history of the D line of sodium. It was first observed by Fraunhofer. But could he suspect that he had the key to all of quantum mechanics in his hands? He saw that the line is split into two components. But could he know that this was the effect of electron spin? The concepts of an "electron", "quantum mechanics" and "spin" had not yet been devised in Fraunhofer's time. Without them, the D line of sodium was simply a curious fact not leading to any consequences. Only after the experiments of Crookes, Rutherford and Thomson, and after the founding of a system of concepts and formulas which was called quantum mechanics, did it become clear that the D line of sodium was one of the facts that alter the very fundamentals of our way of thinking.

Only theory enables us to appreciate the harmony of phenomena in the world of atoms. Any description of the experimental apparatus alone would be hopelessly tedious and uninteresting. Theory is an intuitive penetration into the essence of the observed phenomena. It enables us to guess those of their properties that lie beyond our experience and consciousness, and to explain the seeming complexity of the phenomena by the unseen simplicity. It is precisely this form of thinking that helped the genius of such men as Dalton and Bohr to found modern atomism. Only theory has made the picture of the atom aesthetically acceptable and not only logically satisfactory. Evidently, such moments of penetration into the essence of things have rightly (perhaps by stretching a point etymologically) been called Θεορια—a looking at divinity.

It is common knowledge that concepts are formed on the basis of new facts, but comparatively few people

are aware of the extent to which the meaning of the new facts depends upon the concepts employed to interpret them. With the development and extension of scientific knowledge, this reciprocal influence of facts and concepts gradually increases and the chain of cognition is modified once again:

$$\left\{\begin{array}{c}\text{phenomenon}\\ \downarrow\quad\uparrow\\ \text{observation}\end{array}\right\} \begin{array}{c}\longrightarrow\\ \\ \longleftarrow\end{array} \left\{\begin{array}{c}\text{concept}\\ \downarrow\quad\uparrow\\ \text{formula}\end{array}\right\} \rightarrow \text{image}$$

In our time this interaction has become so strong that it is frequently difficult to separate the facts from their interpretation. The result of this interaction is frequently called the information explosion because of the rapidity with which the uncontrolled reciprocal influence of new facts and concepts lead to real practical consequences.

The complicated interlacement of facts, concepts, formulas and images of science is very difficult or perhaps even impossible to untangle. All attempts of this kind inevitably run into the sacramental question "What came first, the chicken or the egg?"

Immanuel Kant (1724-1804) tried to break out of the logical vicious circle in which concepts depend on the results of experiments, and the interpretation of experiments on the system of concepts. He maintained that several such concepts were given to man "from God", that he was born with them, and that he could find all subsequent truths by combining these primary concepts if, of course, he made no logical errors. Having made this assumption, Kant constructed an orderly and complete philosophy of cognition. The development of physics soon proved, however, that many of Kant's "*a priori* truths", such as space, time, and others, actually have an empirical and most genuine earthly origin, although they have been rein-

terpreted and deprived of concrete features of the images on whose basis they were formed.

No one will ever know the first scientific fact and the first scientific concept which initiated the evolution of modern science. For this reason we more and more often hear from naturalists that they are "describing nature" rather than "explaining nature".

"We now realize, better than previous natural science did, that no reliable starting point exists from which paths extend to all the regions of our cognition, but that all cognition is obliged, to a certain extent, to soar over the fathomless pit. We always have to start somewhere in the middle and, in discussing reality, employ concepts which only gradually acquire a definite meaning owing to their application...." These words of Heisenberg are ones that any physicist agrees with. There are moments in life when each of them wonders how the cognition of nature is nevertheless possible under such conditions.

Einstein often repeated that "the only mystery of the world is its cognizability".

Physical reality is a very profound concept and, like all profound concepts of our language, is not restricted to a unique meaning. This is a primary concept and it cannot be logically defined with sufficient strictness in terms of simpler concepts. It must simply be *accepted* after giving it the meaning dictated by our whole previous life and the knowledge we have acquired. Evidently, this meaning will change with the development of science exactly in the same manner as the meaning of the concept of an "atom".

Our ancestors believed that their five senses furnish them with a true picture of reality because, with their aid, they could avoid real dangers and survive. At this stage of development the consciousness only classified and analysed the data of our senses.

Other times set in, and the consciousness began to create reality by itself. It painted detailed pictures of hell and heaven, and tried to distinctly conceive of the triune essence of God.

Next came a time of cleansing doubt. We could no longer unconditionally believe the data of our senses (we do not sense the motion of the earth but nevertheless it rotates!) and the conclusions of our consciousness must also be checked by experiment (the stars which were previously thought to be the souls of the deceased and the lamps of the angels turned out to be simply distant suns like our own).

With the advent of science the concept of reality has been changed beyond recognition, and the reality of man of the twentieth century is as far from that of the ancient Greeks as the atom of today is from that of Democritus.

The decisive touches to the new picture of physical reality were filled in by quantum mechanics. Perhaps this is the main reason why people wish to understand "what is quantum mechanics?", but not the only one. This wish is even more deep-rooted than a quite natural professional interest. In studying quantum mechanics, a person acquires much more than the special skills enabling him to design a laser or nuclear reactor. A knowledge of quantum mechanics is a certain emotional process that compels one to go through its whole history again. Like any illogical process, it is strictly individual and leaves ineradicable traces in one's consciousness. This abstract knowledge, once acquired, irreversibly influences the whole subsequent life of a person. It influences his attitude toward physics, toward other sciences and even his moral criteria. The study of music probably changes a person in the same way.

You cannot, of course, become a musician by merely

attending concerts, even if you do it daily. To become one you must first persistently play scales for a very long time. In the study of any science there always comes a time when a person must decide whether he is to remain an amateur or will become a professional. In the first case it will be sufficient for him to master the concepts and images of the science and, if possible, to sense their innate beauty. In the second case he is obliged to learn a *trade*. He must study the interrelations of the concepts and the methods of expressing them in the language of mathematics. Unless he does this he will never experience the joy of an expert and a musician.

Having read this book you have learned only the first notes of quantum mechanics and, perhaps, to play several sonorous chords. Only a musician can appreciate the depth of a musical conception, and only a physicist can experience aesthetic satisfaction from the beauty of formulas. Those of you who intend to devote your lives to science may understand this some day. If, however, you have perceived the beauty of the "melody" of quantum mechanics without grasping its "laws of harmony", the task of our narrative has been accomplished.

ROUND AND ABOUT THE QUANTUM

THE QUANTUM OLYMPUS

Alfred Bernhard Nobel, the Swedish scientist and industrialist, who made a fortune from his invention of dynamite, left the Royal Swedish Academy of Science a large sum of money by his will to establish Nobel prizes that are to be awarded annually to those who "have conferred the greatest benefit on mankind

in the field of physics, chemistry, physiology or medicine, literature and peace".

The first Nobel prize in physics was awarded to Röntgen in 1901, and since then the title of Nobel prize winner has become the highest acknowledgement of scientific achievement. It is remarkable that almost each year for thirty years running Nobel prizes have been awarded for discoveries in atomic physics. Such recognition of a quite narrow branch of physics is no mere coincidence; it really has altered our whole outlook.

Among the Nobel prize winners are the names of all the famous physicists that have built the modern edifice of quantum mechanics. Reading the list of scientists so honoured since the turn of the century, we again repeat, in our minds, the fascinating history of this science.

1901

Wilhelm Konrad Röntgen (1845-1923)—"in recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him".

1902

Hendrick Antoon Lorentz (1853-1928) and Pieter Zeeman (1865-1943)—"in recognition of the extraordinary service they rendered by their researches into the influence of magnetism upon radiation phenomena".

1903

Antoine Henri Becquerel (1852-1908)—"in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity".

Pierre Curie (1859-1906) and Marie Sklodowska Curie (1867-1934)—"in recognition of the extraordinary services they have rendered by their joint researches

on the radiation phenomena discovered by Professor Henri Becquerel".

1904

Sir William Ramsay (1852-1916)—"for his discovery of gaseous, indifferent elements in the air and the determination of their place in the periodic system".

Lord Rayleigh (John William Strutt) (1842-1919)—"for his investigations of the densities of the most important gases and for his discovery of argon in connection with these studies".

1905

Philipp Eduard Anton von Lenard (1862-1947)—"for his work on cathode rays".

1906

Sir Joseph John Thomson (1856-1940)—"in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases".

1907

Albert Abraham Michelson (1852-1931)—"for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid".

1908

Ernest Rutherford (1871-1937)—"for his investigation into the disintegration of the elements and the chemistry of radioactive substances".

1911

Marie Sklodowska Curie (1867-1934)—"for her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element".

Wilhelm Wien (1864-1928)—"for his discoveries regarding the laws governing the radiation of heat".

1914

Max Theodor Felix von Laue (1879-1960)—"for his discovery of the diffraction of Röntgen rays by crystals".

1915

Sir William Henry Bragg (1862-1942) and William Lawrence Bragg (born 1890)—"for their services in the analysis of crystal structures by means of Röntgen rays".

1917

Charles Glover Barkla (1877-1944)—"for his discovery of the characteristic Röntgen radiation of the elements".

1918

Max Karl Ernst Ludwig Planck (1858-1947)—"in recognition of the services he rendered to the advancement of physics by his discovery of energy quanta".

1919

Johannes Stark (1874-1957)—"for his discovery of the Doppler effect in canal rays and the splitting of spectral lines in electric fields".

1921

Albert Einstein (1879-1955)—"for his services to theoretical physics and especially for his discovery of the law of the photoelectric effect".

Frederick Soddy (1877-1956)—"for his contributions to the chemistry of radioactive substances and his investigations into the origin and nature of isotopes".

1922

Niels Henrik David Bohr (1885-1962)—"for his services in the investigation of the structure of atoms, and of the radiation emanating from them".

Francis William Aston (1877-1945)—"for his discovery, by means of his mass spectrograph, of the isotopes of a large number of nonradioactive elements, as well as for his discovery of the whole-number rule".

1923

Robert Andrews Millikan (1868-1953)—"for his work on the elementary charge of electricity and on the photoelectric effect".

1924

Karl Manne Georg Siegbahn (born 1886)—"for his discoveries and research in the field of X-ray spectroscopy".

1925

James Franck (1882-1964) and Gustav Ludwig Hertz (born 1887)—"for their discovery of the laws governing the impact of an electron upon an atom".

1926

Jean Baptiste Perrin (1870-1942)—"for his work on the discontinuous structure of matter, and especially for his discovery of sedimentation equilibrium".

1927

Arthur Holly Compton (1892-1962)—"for his discovery of the effect named after him".

Charles Thomas Rees Wilson (1869-1959)—"for his method of making the path of electrically charged particles visible by the condensation of vapours".

1929

Prince Louis-Victor de Broglie (born 1892)—"for his discovery of the wave nature of electrons".

1932

Werner Karl Heisenberg (born 1901)—"for the creation of quantum mechanics, the application of which has, among other things, led to the discovery of the allotropic forms of hydrogen".

1933

Erwin Schrödinger (1887-1961) and Paul Adrien Maurice Dirac (born 1902)—"for the discovery of new productive forms of atomic theory".

1934

Harold Clayton Urey (born 1893)—"for his discovery of heavy hydrogen".

1935

Frédéric Joliot-Curie (1900-1958) and Irène Joliot-Curie (1897-1956)—"for their synthesis of new radioactive elements".

1937

Clinton Joseph Davisson (1881-1958) and Sir George Paget Thomson (born 1892)—"for their experimental discovery of the diffraction of electrons by crystals".

1945

Wolfgang Pauli (1900-1958)—"for the discovery of the Exclusion Principle, also called the Pauli Principle".

1951

Edwin Mattison McMillan (born 1907) and Glenn Theodore Seaborg (born 1912)—"for their discoveries in the chemistry of the transuranium elements".

1954

Max Born (1882-1970)—"for his fundamental research in quantum mechanics, especially for his statistical interpretation of the wave function".

Linus Carl Pauling (born 1901)—"for his research into the nature of the chemical bond and its application to the elucidation of the structure of complex substances".

1955

Willis Eugene Lamb, Jr. (born 1913)—"for his discoveries concerning the fine structure of the hydrogen spectrum".

Polykarp Kusch (born 1911)—"for his precision determination of the magnetic moment of the electron".

1958

Pavel Alekseevich Cherenkov (born 1904), Ilya Mikhailovich Frank (born 1908) and Igor Evgenyevich Tamm (1895-1971)—"for the discovery and the interpretation of the Cherenkov effect".

1961

Rudolf Ludwig Mössbauer (born 1929)—"for his research concerning the resonance absorption of γ-radiation and his discovery in this connection of the effect which bears his name".

1962

Lev Davidovich Landau (1908-1968)—"for his pioneering theories for condensed matter, especially liquid helium".

1964

Nikolai Genadievich Basov (born 1922), Alexandr Mikhailovich Prokhorov (born 1916) and Charles Hard Townes (born 1915)—"for fundamental research in quantum electronics resulting in the creation of masers and lasers".

Speculation

Part Three

Chapter Twelve

INCEPTION OF THE SCIENTIFIC METHOD * ESSENCE OF THE SCIENTIFIC METHOD AND ITS DEVELOPMENT * TRUTH AND COMPLETENESS OF THE SCIENTIFIC PICTURE OF THE UNIVERSE * SCIENCE AND HUMANITY * BOUNDARIES OF THE SCIENTIFIC METHOD * SCIENCE AND ART * FUTURE OF SCIENCE

Recently, in the heat of an argument, a physicist declared: "In principle, a knowledge of Coulomb's law and the equations of quantum mechanics alone is enough to describe even such a complex system as man."

Such statements have been made before in science. A lever was all that Archimedes needed (and a place to stand on) to move the earth. Laplace undertook to predict the future of the world if he were furnished with the initial coordinates and momenta of all the particles in the universe. Although such a firm faith in the completeness and omnipotence of science is alluring, it does not pay to forget the warning of Friar Roger Bacon which is just as true today as it was seven hundred years ago. He wrote: "If a man lived in this mortal vale even a thousand centuries he would still never reach perfection in knowledge; he doesn't know the nature of a fly, but certain presumptuous scholars believe that philosophy has been completely developed."

Friar Roger Bacon (1214-1294) was a Franciscan monk who studied and taught in Oxford, one of the first universities of the world; it had been founded not long before his birth.

"There exist four supreme obstacles to the comprehension of truth," he wrote. "They hinder all and each wise man, and hardly allow genuine wisdom to be attained. They are: the example of a paltry and unworthy authority, the constancy of habit, the opinion of the ignorant multitude, and the cloaking of one's own lack of knowledge by pretentious wisdom."

Some time between 1277 and 1279 Roger Bacon was condemned to prison by his fellow Franciscans and he spent several years there.

This was the age of the Crusades, a time when religious dogmas flourished and were merged with philosophy and Christian mysticism. Theology became the foundation of learning, the lives of the saints were depicted as moral and ethical models, and the authority of the church was so high that the popes contended with kings for temporal power. Nothing seemed to betoken the downfall of the whole system of medieval

spiritual values. Nevertheless, religious faith soon gave way to scientific knowledge and mystical insight to rational experiment.

We are witnesses of the flourishing of a new system of values that trusts nothing but experiment and is based on science. The might of science amazes even experienced minds. It has split the atomic nucleus, reached the moon, discovered the laws of heredity....

Although we all sing the praises of scientific achievements, relatively few of us understand the essence of the scientific method, know the reasons for its efficacy or, all the more, have an idea of its limits. No science of science has yet been founded and we don't know whether one exists. But, even if we do not know the laws governing the development of science, it is always of interest to retrace its sources and characteristic features. This will help us to understand the place and role of quantum mechanics in the general system of human knowledge.

INCEPTION OF THE SCIENTIFIC METHOD

We have lost the knowledge possessed by the ancients, only its fragments have reached us. But they are unsystematic, alien to us in essence, and seem to be naive. The ancient Greeks are considered the source of the science of today. They are our forerunners in spirit, which is the main factor, and not only in time. The Greeks invented *proof*. No such idea occurred in either ancient Egypt, or Mesopotamia, or China, probably because tyranny and absolute subordination to the authorities reigned in those states. Under such conditions, even the thought of reasonable proof alone sounded seditious.

For the first time in the whole history of mankind, a republic was established in Athens. There is no need

to idealize it inasmuch as it flourished on the labour of slaves. Nevertheless, conditions were established in ancient Greece that made a free exchange of opinion possible, and this led to an unprecedented growth of science. Rudiments of the scientific method were evolved; with its aid the Greeks tried to construct a picture of the universe as a whole.

The necessity for a rational cognition of nature became entirely extinct in the Middle Ages, which was the time of attempts to comprehend the place of man in the world within the limits of the various religious dogmas. For almost ten long centuries religion furnished exhaustive answers to all questions of life. These answers were not to be subject either to criticism or to discussion, and reason was unconditionally subordinated by faith.

Euclid's works were translated into the Latin and became known in Europe in the twelfth century. At that time, however, they were considered to be simply a set of witty rules which were to be learned by heart, so alien were they to the spirit of medieval Europe which was accustomed to believe rather than to look for the roots of truth. But the scope of knowledge widened rapidly and it could no longer be coordinated with the trends of medieval thought.

The end of the Middle Ages is usually associated with the discovery of America in 1492. Certain historians cite an even more precise date—December 13, 1250—the day when Frederick II Hohenstaufen, Emperor of the Holy Roman Empire, died in the castle of Fiorentino near Lucera. These dates should not be taken too seriously, of course, but several such dates, when taken together, impart an unquestionable feeling of authenticity to the fundamental change that occurred in the consciousness of people at the turn of

the fourteenth century. In history the period that followed is called the Renaissance.

Conforming to internal laws of development, and without any apparent reasons, Europe took only two centuries to revive all the beginnings of ancient knowledge that had been neglected for over ten centuries and that were subsequently given the name of scientific knowledge.

The change that occurred in the minds of people during the Renaissance made them turn from the striving to realize their place in the world to attempts to understand its rational structure without references to miracles and divine revelations. At first this upheaval was of an aristocratic nature, but the invention of printing, "an invention more likely divine than human", spread it to all sections of the population.

The essence of this Revival of Learning was in the freedom from the oppression of authority and the transition from medieval faith to knowledge. The church resisted these new trends in every possible way. It severely persecuted philosophers who maintained that there were things which are true from the viewpoint of philosophy but false from the viewpoint of faith, "as if," as the Church put it, "in contradiction to the truth in the Scriptures, there could be truth in the books of the heathens".

If we disregard the political passions of the time in which Galileo lived, it becomes clear that he was tried and condemned not only for his sympathy to the Copernican theory. The same ideas were advocated a century earlier by Cardinal Nicholas of Cusa (1401-1464) and he went unpunished. The difference is that the learned cardinal *asserted* these ideas, referring to the pertinent authorities as was befitting to a true believer; Galileo went about *proving* the

same ideas, as is required by science. He suggested that each person could check the truth by experiment and common sense. This is just what the Church could not forgive him for.

But it was soon impossible to patch the collapsing bulwark of the faith, and the liberated spirit began searching for new paths of development.

After being held so long under the oppression of authorities, the scholars of the day rushed to the other extreme; a period of general doubt began. Practically everything was subject to doubt: that our senses provide a correct idea of the world and that the consciousness is able to protect itself against errors in opinions and feelings. They even doubted the reality of their own existence.

This was a time when the support of faith was lost but a confidence in reason had not yet been acquired. Moreover, it seemed that the imperfection of the mind had put off the hope of ever reaching the truth through cognition. Only gradually did reason gain power and a method was devised, step by step, that could protect it against its own mistakes.

Scholars searched for the *principles* of scientific knowledge, and the *method* by which they could be realized, long before the advent of modern science. As far back as the thirteenth century, Roger Bacon wrote in his treatise *Opus tertium*:

"There exists natural and imperfect experience that does not realize its power and is unaware of its procedures: it is used by craftsmen, not by scientists.... Higher than all speculative knowledge and art is the skill of conducting experiments, and this science is the queen of sciences....

"Philosophers should know that their science is helpless if they do not apply powerful mathematics to it.... It is impossible to distinguish a sophism from

a proof without checking a conclusion by means of *experiment* and *application*."

In 1440, Cardinal Nicholas of Cusa wrote a book called *De docta ignorantia (On Learned Ignorance)* in which he insisted that all knowledge of nature should be written in numbers and all experiments on it should be conducted with scales.

The consolidation of the new views proceeded slowly. For example, although Arabic numerals were put into general use as far back as the tenth century, even as late as the fourteenth century all calculations were carried out by means of special counters rather than on paper. These counters were even less efficient than a Chinese abacus.

It is customary to begin the real history of the scientific method with Galileo and Newton. According to the same tradition, Galileo Galilei (1564-1642) is considered to be the father of experimental physics and Sir Isaac Newton (1642-1727) the founder of theoretical physics. In their time, of course, the united science of physics was not divided into two parts, there wasn't even any physics as such, it was then called natural philosophy. But such a division has a profound meaning. It enables us to understand the specific features of the scientific method, and is equivalent to the division of science into experiment and mathematics as formulated by Roger Bacon.

ESSENCE OF THE SCIENTIFIC METHOD AND ITS DEVELOPMENT

We have become so used to identifying the concepts "knowledge" and "science" that we cannot conceive of any other knowledge than scientific knowledge. What are its essence and distinctive features?

The essence of the *scientific method* can be explained quite simply. This method enables knowledge to be obtained on phenomena that can be *checked*, *preserved* and *passed on to somebody else*.

From this it follows that science does not study phenomena in general; it studies only those that are *repeated*. Its main task is to find the *laws* governing these phenomena. This task was accomplished by science in different ways at different times.

The ancient Greeks attentively *observed* phenomena and then by means of speculation tried to gain an insight into the harmony of nature by the power of their intellect, relying only on the data of their senses accumulated in their memory.

It became evident during the Renaissance that the goal set in the study of nature could not be reached by means of the five senses alone. It was necessary to invent instruments which are none other than extensions and intensifiers of our sensory organs. Then two questions arose: to what extent can we trust the readings of instruments and how are we to store the information obtained with them?

The second problem was soon solved through the invention of printing and the systematic application of mathematics in the natural sciences. It was much more difficult to solve the first problem concerning the reliability of knowledge obtained by instruments. In essence, a final solution has still not been found, and the whole history of the scientific method is one of its continual extension and modification.

It did not take long for scientists to understand that the readings of instruments can be trusted, as a rule, that is that they represent something real in nature that exists independently of the instruments. (Scientists were finally satisfied that sunspots are really spots on the sun and not defects of the telescope used

to observe them.) The knowledge accumulated during this period when experimental physics flourished became the basis for the powerful breakthrough in engineering at the end of last century.

But the volume of knowledge increased at a headlong pace and led to a crisis in physics at the turn of the century. Its main point was that at a certain moment physicists could no longer understand how they were to correlate the figures obtained by means of instruments with the real phenomena in nature. At precisely this moment theoretical physics became of prime importance.

There were two reasons for the crisis. On the one hand, the instruments had left the immediate sensations of man too far behind and therefore intuition, based on the readings of the instruments, could no longer provide any simple picture of the observed phenomena. All the possibilities of achieving a visualizable interpretation of the experimental data were thereby exhausted.

On the other hand, no logical scheme existed by means of which the scientific facts could be orderly arranged and which would lead, without referring to intuition alone, to such observable consequences that could not be refuted even by common sense.

The crisis was overcome. Physicists continued to trust the readings of instruments, but devised new concepts and new logical schemes which taught them to interpret these readings in a new manner. Quantum mechanics played the decisive role in breaking down the established concepts. It did not just endow us with the power to control the entirely new world of atomic phenomena. It did more. Quantum mechanics convinced us that the readings of instruments are not simply photographs of phenomena in nature. They are not concerned directly with nature but only represent

some aspect of these phenomena together with our ideas of nature and fix them with numbers.

In the course of time this knowledge becomes more profound and enables us to predict finer and finer phenomena of nature. This fact is amazing in itself and we shall probably never fully understand it but, since it has become known, we make use of it.

Almost all physicists agree now with this viewpoint, but they want to understand something more: just how complete is the picture of the world drawn by physics. This is a philosophical rather than a physical question. It arose many a time throughout the history of mankind but was first clearly formulated in Plato's dialogues.

Plato likened scientists to prisoners chained in a cave with their backs to the entrance. They could see no light; they could only see shadows moving along the opposite wall. He admitted that even under such conditions it was possible, by attentively observing the motion of the shadows, to learn to foresee the behaviour of the bodies whose shadows were visible on the cave walls. But knowledge acquired in this manner is still infinitely distant from the complete knowledge acquired by a freed prisoner when he comes out of the cave.

Plato's argument cannot be refuted. The world around us is really much more splendid than the one we can conceive on the basis of data provided by physics. A person who was born blind can learn everything there is to know about optics, and yet he will never have the slightest idea about what light is, let alone the splendour of colour in spring. When we enter the world of atomic phenomena we are very much like people who were born blind, since we are completely deprived of "atomic sight" and can only grope our way in this unusual world.

Similar analogies are numerous and each one teaches physicists to be more modest. In the nineteenth century they hoped to *explain* nature; in the twentieth century they strive only to *describe* it. We understand now that questions concerning the completeness of physical knowledge and the essence of phenomena are not within the scope of physics and cannot be answered by physical means. Physics studies only the laws according to which these phenomena occur. In this sense it exactly follows the "theory of shadows".

This is merely a restricted knowledge of nature. But how true is it?

TRUTH AND COMPLETENESS OF THE SCIENTIFIC PICTURE OF THE UNIVERSE

The problem cannot be solved logically. We *believe* in science because it enables us to correctly predict phenomena of nature and because it does not depend upon the personal arbitrary wishes of the investigator. We may question the structure of its images. They depend upon the method of communicating our ideas. But we are certain now that all terrestrial and celestial bodies consist of the same elements in approximately the same proportions. We are also certain that the laws of nature are the same throughout the universe and, consequently, an atom of sodium will always radiate the same D line wherever it is, on the earth or on Sirius. This is now admitted almost universally, and no one doubts the truth of *this* knowledge. Doubt arises when on the basis of particular, although firmly established, facts we attempt to create a general and consistent picture of the world, one that agrees with the totality of experimental data and the general nature

of human consciousness. The most frequent question is: how unique is the *form* of physical laws?

There is no explicit answer to this question. Those acquainted with the history of science know that in certain periods of its development two theories existed, side by side, each considering itself to be true and each being an equally good explanation of the phenomena known at that time. The same history relates, however, that in the course of time new experiments selected only one of the two theories or, in a new stage of development, they merged together on the basis of newer and more significant principles, as in the case of the corpuscular and wave theories of light.

Facts and concepts of science may seem random if only because they have been established at random times by random people and often in random circumstances. But, when taken together, they form a single regular system in which the number of relationships is so great that you cannot replace a single link without affecting all the others. This system is continually changed under the pressure of new facts and becomes more accurate but never loses its integrity and distinc-

tive completeness. Taken as a whole, the system of scientific concepts is the product of long evolution. For many years old links were replaced by new improved ones, and entirely new concepts were always formed with due regard for or on the basis of the previous ones. In short, science is a live developing organism rather than a congealed schematic diagram. Although all the concepts of science are creations of human reason, they are nevertheless random to the same extent that the most intelligent life in nature is random.

In one of Ray Bradbury's science-fiction stories, the hero takes a trip on a time machine into the dim past. During his short visit he accidently squashes a small butterfly. When he returns to the present time he does not recognize the world he departed from. It seems that his involuntary and, at first glance, negligible intrusion into the course of biological evolution has completely altered all its final results.

This example is evidently no more than a spectacular extreme pardonable in the works of a science-fiction writer. There is no doubt that everything in nature is interrelated, not with such a severe causality, however, bordering on determinism, but more resourcefully and flexibly, like the statistic causality of quantum mechanics. (Nevertheless, this example warns us once again against any intrusion into nature because no one can foresee the remote consequences of such actions.)

The evolution of the system of scientific concepts is just as uncontrolled, but regular, process as the evolution of the animal world. We can imagine it as being different in particulars, we can wonder at its strange whims, but we cannot imagine it as being entirely different. We don't know how the first concept and how the first organism were formed, nor

what they would have become if they had been quite different. But we do know that each successive step in evolution depended on all the previous ones. Therefore we can readily imagine a horse with tiger's paws or an atom in the form of a doughnut, but to imagine an entirely different animal world and system of scientific concepts is beyond our powers. Both the process of biological evolution and the formation of scientific concepts conform to their intrinsic laws which we cannot change and of which we do not yet have complete knowledge.

We are born into a world of species that have already formed and of concepts that have already been established. We can breed a new strain of horses or replace one concept with another one which will agree better with scientific truth. The problem, however, of the truth or falsity of the *whole* system of human knowledge is outside of the sphere of consciousness and cannot be solved by its means. And what is more, this problem is devoid of sense. Science was created by man and for man, and its whole system of concepts has been devised to conform to the nature of human consciousness. The ultimate aim of a concept is to predict and explain phenomena that act on our sensory organs or on their extensions—instruments.

Almost certainly intelligent beings exist somewhere in the universe; their sensory organs differ from ours and their consciousness has a different structure. Their system of concepts may also fundamentally differ from ours. But even if we were able to understand their system sufficiently well to compare it with ours, we would not be able to conclude from this comparison that their system is false. On the contrary, it should always be true if it provides its sensory organs with correct prediction. Our scientific knowledge of the world is no more than real shadows of real pheno-

mena of nature, the shadows that are illuminated by the light of our consciousness. The same object can cast different shadows depending upon the angle at which it is illuminated. In exactly the same way the system of scientific knowledge created by intelligent life on another planet can be different from ours. It may be that some day, not very soon, we will have the opportunity of comparing these "conscious shadows" and, like Plato's prisoner after escaping from the cave, use them to restore truth in all its completeness and magnificence as a skilled craftsman makes a three-dimensional machine component from several plane projections of the part drawing. But for the time being we must extend our science of today. Despite all its imperfections, it is the only method available so far for penetrating deep into the observed phenomena.

The world is objective and exists independently of our consciousness. It is no concern of the world how we, a part of this world, conceive of the internal mechanism of its external manifestations. This is of importance only to us ourselves. This is not the point; the question is: how far can we advance along this road? And how long can we continue to refine our conceptions about the causes of the observed phenomena? Instead of the problem of physical reality, we should determine the boundaries of the scientific method. This is the problem that has become especially urgent after the founding of quantum mechanics.

SCIENCE AND HUMANITY

It is customary to consider that science (in the present meaning of the word) has existed not over 300 or 400 years. In this very short period science has completely changed the mode of life of all civilized peoples,

their attitude toward the world, their method of thinking, and even their moral categories.

The main feature of the new philosophy of life is the awareness of continuous motion in the world and, as a result of this feeling, a striving to find out about and understand the surrounding world so as to appropriately respond to its changes. Modern man regards once and forever established principles sceptically; he doesn't believe that any knowledge may be final: each moment of his life he is in a perpetual state of search for some optimal solution. The insatiable thirst, for knowledge, first provoked during the Renaissance, has not yet been satisfied. The scientific method has transformed the world in which we live. It has populated this world with machines and we often regard them as living beings; it has helped people to feed themselves and protected them against disease. This has brought about an unprecedented growth in the population.

The successes of the scientific method have led to the origination and consolidation of a new belief, a belief in science which sometimes reminds one of the medieval faith in divine revelations. The change wrought by science in the minds of people is comparable only with such great religious upheavals as Buddhism, Christianity and Islam. Science has taken the place of religion both in form and in essence. Science is expected to give answers to all questions of our life, its verdicts are regarded as infallible, models to mould one's life after are selected from its votaries, and the number of its followers grows faster than did the army of Buddhist monks in the East in ancient times. But in contrast to previous religions which gave certain people power over others, science gives man power over nature.

The countries of the Occident that adopted this new

religion have left the formerly flourishing countries of the Orient far behind. This became possible due to a simple discovery: the essence of many phenomena of nature can be written down in the form of numbers and equations establishing the relationships between the numbers. Like any systematic method, the scientific method has its costs, range of action, and boundaries of applicability.

In ancient times it was not considered an unworthy occupation for a man to sit on the seashore and watch the sun describe its great circle across the heavens. Much has changed since then. Inductive sciences have replaced pure speculation and have undertaken to "verify harmony by means of algebra". Science took its stand on the firm foundation of experiment but lost its traits of serene wisdom and leisurely contemplation. One can lament over this but it is already impossible to change anything.

In its early days only lone devotees were occupied with science, and at their own peril. For a long time the results of science were not considered obligatory for everybody. Even as late as the middle of last century Faraday made an appeal to have science recognized as an element of general education. In our time science has acquired a mass character, and scientific work is a most ordinary, and frequently humdrum, occupation. Science has become a material force rather than a means of cognition, but at the same time it has come into contact with human passions far less noble than those to which it owes its origin.

All of this is true, all of this is so, but in the age of science it is inconceivable to give up its results merely from moral considerations. In a striving for cleanliness we should not go beyond the limits of sterility. The principal requirement made to musicians is that they play well. Whether they are also gamb-

lers or not is simply a matter of luck. So far science does its work well. It builds machines, feeds mankind, supplies it with energy, and protects it against disease. This, of course, does not release scientists from their moral responsibilities for their, sometimes deathly, discoveries.

Mutations are known to occur in the process of biological evolution from time to time. Some of them rapidly take hold and supplant less fitted traits. But the others remain latent and become apparent only when a change in external conditions threatens to destroy the biological species. It is exactly these latent mutations that once saved the human race from extinction. But evolution has not ceased; it has only changed its forms. For thousands of years the body of man has remained almost the same, but his consciousness has changed beyond recognition and irreversibly. Under these conditions, science serves as a source of new ideas that may save mankind some day from impending catastrophes.

The scientific method is an agreement between people that is sufficiently fruitful to become universal. On the basis of this agreement a kind of collective intellect has been formed and is being developed. Although it may not be immortal, it is evidently comparatively long-lived. How long it will last and where the boundaries of the scientific method are, we do not know yet. But the fact that such boundaries exist is beyond all question.

BOUNDARIES OF THE SCIENTIFIC METHOD

Man has always been preoccupied with the "eternal questions" of life and death, good and evil, God and eternity, the final aim of life and the place of man in the universe. Religion could not answer these ques-

tions. It could only allay for a time the longing to know the answers, and provided mankind with a brief consolation through forgetting the complications of life on this earth.

Science is also unable to answer questions on the purport of life; it has more modest tasks. We often forget this when we are blinded by the successes of the exact sciences and do not take into account the possibility that our rationalism and belief in science may be just as absurd and incomprehensible to future generations as the ceremonial rites of ancient Egyptian priests are to us. Only cognition itself, and not its historical forms, is without limit.

Science is able to gain knowledge only of phenomena whose properties can be assessed by numbers. The performance of a hypnotist cannot be described by means of mathematical formulas, and yet its results are doubtless and reproducible. The accomplishments of Hindu yogis are experimental facts and have been repeatedly checked, but they cannot, however, become the objects of exact science because they do not lend themselves to a quantitative description by means of numbers and formulas. In exactly the same way, the phenomenon of telepathy cannot become a fact unless it is confirmed by scientific experiments. Only proofs with references to the pertinent authorities were taken into account in the Middle Ages, but now we believe nothing but experimental proofs.

It doesn't pay to grieve over this. This simply means that our world is richer and more complex than the image provided by science. A smile doesn't cost anything but, fortunately, nothing can replace it. This is always a useful thing to remember to avoid wallowing in learned ignorance. Those of the scientists who attempt to conceive of the world in the form of endless tables of numbers and deny the reality of many phe-

nomena of nature only because they are inexplicable by scientific means do not greatly differ from priests who used to close their eyes when they saw a locomotive, stamp their feet and cry, "Get thee behind me Satan!" Such scientists find that a genius and a murderer are indistinguishable because they can *scientifically* prove that they consist of exactly identical molecules.

With such discourse as a background, quantum mechanics, about which we have found out so much by now, should seem to be an entirely simple science. Indeed, we know so much about the hydrogen atom that we can predict all its observable phenomena. It is considerably more difficult, but still possible, to calculate the properties of a hydrogen molecule. We are unable, however, to predict the properties of a protein molecule. There are not so many different proteins although each person, in all his uniqueness, is composed of them.

In short, science is beneficial and even necessary, but necessity should not be converted into a virtue, and there is no need to subordinate everything to science only because we cannot do without it for the time being.

SCIENCE AND ART

The limitations of science are the most evident in attempts to use scientific methods in unveiling the secrets of art. Science "knows everything" about a grand piano: the number, quality and the length of its strings; the species of wood used; the composition of the glue, and the finest details of its design. Nevertheless, it is unable to explain what happens to this polished box when a virtuoso sits down to play. Perhaps this is unnecessary. A person who cries over a

book does not usually ponder over the means the author used to accomplish this effect. He can, of course, later read a critical work, twice as thick, on the book that made such an impression on him. All this, however, will resemble the dissection of a cadaver in an anatomic theatre; it is necessary for specialists but extremely unpleasant for most amateurs. (Marcus Aurelius used to repeat that "to despise singing and dancing, it is sufficient to decompose them into their component elements".) But Art is wise; through all the ages it has guarded the ingenuousness of sensual perceptions from the persistent intrusions of science. Art has always been valued precisely for this capacity to "remind us of harmonies inaccessible to systematic analysis".

Anyone who wishes can understand the design of a nuclear reactor even if he has never seen one. But it is absolutely impossible to explain to a person what charm is if he has never been enchanted.

The source of the might of science is its universality. Its laws are free of the arbitrariness of various people. It represents only their collective experience, independent of age, nationality or frame of mind. The secret of art is in its inimitability. The power of its influence depends on the whole previous experience of man, on the wealth of his associations, on elusive changes in moods, on a chance glance, word, or touch—on all that constitutes the force of individuality, the beauty of the transient and the power of the inimitable.

The highest achievement of a scientist is to have the results of his work confirmed, that is to have some one obtain the same results in the future. In art repetition is equivalent to death, and a great actor dies on the stage in a new way in each performance.

There have been cases when symphonies were com-

posed by persons not having even the rudiments of musical knowledge. These symphonies may have been unusual but were eligible as such if at least one listener liked them. Such a situation is inconceivable in science. It has a criterion of truth and the word "likes" has been excluded from its vocabulary.

In science truths are proved and phenomena are explained. In art they are interpreted. Logical reasoning is alien to art which substitutes the spontaneous cogency of images for rigorous proofs.

As a rule, science can always explain why this formula is good or why that theory is bad. Art only permits one to feel the fascination of music or the brilliance of a sonnet, and never explains anything completely.

Science originated at the moment when people learned to single out simple regularities from the chaos of random facts. But art begins only when we put together things that are simple and natural and suddenly become aware of a miracle.

Science is thorough and unhurried; it keeps on solving its problems for years on end, and many of them are often passed over from generation to generation. It can afford this luxury because of an unambiguous method that has been devised for recording and storing the facts established by science. In art the intuitively precise world of images lives but a single instant. (Great actors are sometimes called "heroes of the fleeting moment".) This is sufficient, however, to awake in the hearts of people an echo that will persist for years, and that sometimes even changes the whole course of their lives. "Then would I hail the fleeting moment/O stay—you are so fair!" was Faust's passionate longing that can be fulfilled only by the magic of art. Due to this magic, after a lapse of many years, the memory of man can renew with frightening

clarity the nuances of remote thoughts and moods, that are inexpressible in words.

Notwithstanding the seeming fragility and ambiguity of images of art, it is more durable and ancient than science. The Gilgamesh Epic and Homer's poems do stir us even now because they tell of something that is vital in man and that has remained unchanged for thousands of years. As for science, it has hardly had time to consolidate the new possibilities of reasoning that have only recently been opened to mankind. It is almost impossible today to read books of physics written in the last century, so obsolete they have become and so much has the whole style of scientific thought changed since then. The importance of scientific works is determined by their fruitfulness, and not by their longevity. They have already done their bit if, in their time, they implemented the advancement of science.

We can go on searching for and finding endless shades of distinction between art and science. This subject is inexhaustible, but the benefit of such an occupation is doubtful, since, in fact, they differ only in the methods they use to gain a knowledge of the surrounding world and human nature, and not in essence. In ancient Greece the two notions were not distinguished and a single word τεχνη (*techne*), meaning "skill", "art", "craft" and "refinement" (also the root of "technology") was used to denote them.

Poets have long been searching for a "poesy of thought" and not simply poetry. Scientists, on their part, undertake to explain "poetry in science" to interested listeners. Both, it seems, have come out of hiding to break down the artificial borders between their clans and to forget their ancient feud about the antiquity of their kin. There is no sense in arguing about which hand, the right or the left, is the more important,

even though they develop and function differently.

Any actor understands that he cannot reach the summit of his art before the masters he sciences of diction, mimicry and gesture. And only then, quite unconsciously (provided he is talented, of course) can he create from these simple and comprehensible elements something inimitable and wonderful.

In exactly the same way, a scientist, even though he has mastered the trade of a physicist, is no physicist as yet if he trusts only in formulas and logic. All profound truths of science are paradoxes at birth and cannot be attained only on the basis of logic and experiment.

In short, real art is impossible without the most rigorous science. Likewise, the method of discovering profound scientific truths is beyond the scope of science and belongs entirely to the sphere of art. But there are always boundaries to the scientific analysis of art, and there is always a limit which does not permit science to be comprehended by a single transport of inspiration.

There is an apparent complementarity in the methods used by science and art in the process of cognition of the surrounding world. The workaday method of science consists in the *analysis* of facts and a search for their causes, a striving to "... find eternal law in the marvellous transmutations of chance", and to attempt to "... seek out the fixed pole in the endless train of phenomena". Predominant in art is unconscious *synthesis* which from the same "transmutations of chance" finds the only and the inimitable and from the same "endless train of phenomena" infallibly selects only the ones that enable the harmony of the whole to be sensed.

Only recently have the useless arguments died down

between the "physicists" and "lyricists" (the former denoting people who feel that science and engineering have left little place in our modern world for poetry and art in general, and the latter being the opposing faction which are not to be confused with the usual meaning of the word, i.e. people who write the words of popular songs). The incomprehensible vehemence of the arguments can only be explained by the insufficient competence of the squabblers. The process of creative work (but not the trade!) is the same both in physics and poetry. A poet first feels a vague sensation of rhythm and the swing of his lines of verse. Only later does he find (consciously this time) suitable words and a form to express what he wants. A physicist first conceives a vague general picture of the phenomenon, which he often cannot even tell about in words. Only later does he subject this amorphous, speculative, and yet to some extent, integral and synthetic, image to logical analysis, separate it into concepts, fix it in the language of formulas and, finally, check it by experiments.

The chain "image—concept—formula" varies for different scientists, and may differ in its power, rapidity and strength. Many factors influence this chain: the scientist's path of development, his previous guesswork and errors, his accumulated knowledge, his sense of the language, and even his temperament. Some scientists have a curtailed chain. There are, for example, many scientists that are rarely visited by images. But those who possess the whole chain of interrelations acquire the capacity, at some stage, for aesthetically appraising the final results of science. For them the concepts of a handsome formula, an elegant calculation, or a witty hypothesis sound natural and are full of meaning. For them art is not only the initial stimulus in science; it is, at the same time, the result

in its highest manifestations. This does not mean, of course, that they draw a musical clef instead of an integral sign, and it is only in poor novels that a scientist, on hearing music, remembers that the octaves are based on logarithms.

The world of human perception is infinitely diverse, but it is chaotic and coloured with personal emotions. Man strives to put his impressions in order and to coordinate them with the impressions of others. For this purpose he has invented science and created art. This yearning prompted the inception of both art and science. They are united by the feeling of wonder that they evoke: *how* did this formula, this poem, this theory, or this music come into existence. ("The beginning of knowledge is wonder", they said in antiquity.)

The aesthetical perception of the logical beauty of science is inherent in some form in each genuine scientist. Precisely this feature enables them to perceive nature "like an artist who selects among the innumerable lines of his model only those that impart life and beauty to it".

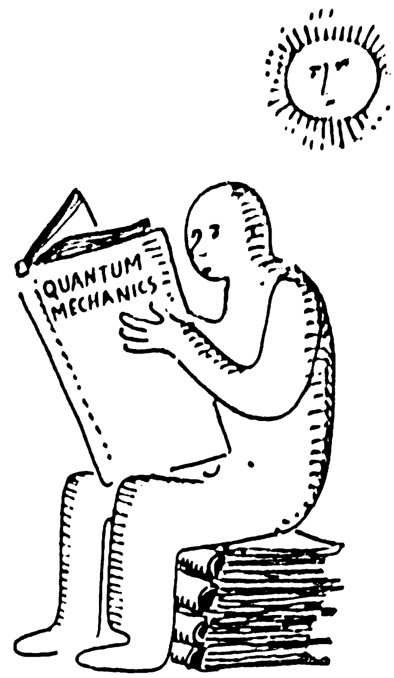
The nature of creative work is the same in all arts and sciences. It is determined by the intuitive capacity to group facts and impressions of the surrounding world so as to satisfy our emotional need for the feeling of harmony that a person experiences when out of the chaos of external impressions he has singled something that is simple and fully complete. This may be a statue made of marble, a poem composed of words or a formula expressed in numbers. This emotional satisfaction is, at the same time, the first criterion of the genuineness of what has been created which, of course, is to be subsequently tested, by experiments in science and by time in art.

When one thinks of the future of science, one imagines a world of machines, push buttons, and transparent domes. In short, one imagines a world of *things* which are controlled by a man in a spotless white outfit. The same mistake is made by most people after a superficial acquaintance with quantum mechanics. As a rule, they are amazed by the concrete, coarse, and visible end products of quantum mechanics, such as the atomic bomb, nuclear-powered ice-breaker, or nuclear power station. Only a few surmise that all these items are but simple consequences of quantum mechanics. What really should amaze us is the wonderfully simple and harmonic system of scientific *ideas* of atomic physics owing to which the ice-breaker, power station and, unfortunately, the bomb have become feasible.

No one can speak of the future of science without the risk of lapsing into naivety or overstatement. It is easy to demonstrate the limitations of the scientific method in a field where it is inapplicable, but it is impossible to predict its potentialities.

Undoubtedly, the scientific mode of thinking is but one of the faculties of human consciousness which, however, has not yet been exhausted. It is quite probable that in the future man will discover in himself new abilities for cognizing the surrounding world, and that this will enable him to better understand his place in this world. But this new, more perfected knowledge will undoubtedly comprise all the principal achievements of science.

We can only guess what this new knowledge will be like. Man can always do more than he thinks he is able to. It may be that the time will come when the capacity for synthetic cognition will again develop



in man to a new and higher level. It was this capacity that distinguished the wise men of ancient times, and that has now become almost extinct on the background of successes of scientific analysis. Perhaps in the future intuition will be converted from a means of scientific foresight into an instrument of scientific proof. There is nothing incredible in this. We do trust the eyes of a diamond sorter although they differ from ordinary eyes only because of their long training. Perhaps, the time will come when we likewise will learn to train our intuition and to cultivate it in different people. If we actually succeed in this, all questions about the ambiguity of scientific concepts and the whole cumbersome apparatus of logic will by itself become unnecessary. It is impossible to foresee the consequences of such a revolution in thought.

There are plenty of hypotheses on the future of science. There is a full spectrum of them, from unrestrained enthusiasm to the most gloomy pessimism. Some foretell imminent downfall of all of our civilization due to unskilful employment of the forces that have been called forth by the same civilization. Others

believe that mankind will still exist even when our sun becomes extinct.

But no matter how mankind develops in the future—granted that it continues to exist—it will always recall our impetuous and stormy age of science with amazement, much as we now recall the Renaissance or the times of the sages of antiquity.

CONCLUSION

In my youth I often pondered over the fact how the reading of good books—a nonmaterial process—could change the whole aspect of a person beyond recognition: his speech, his smile, the expression of his face and eyes, and even his gait and gestures. Only little by little did I understand that this is one of the main and still unsolved riddles of human consciousness.

When the savage nomads branded their herds of horses with red-hot irons they didn't know that the spectrum of radiation of the branding iron conformed with Planck's formula. Bathing their horses in a river they did not imagine the molecules of water to be isosceles triangles with a vertex angle of 109 degrees and 30 minutes. When they came out of the river, they never gave a thought to the fact that the tan of their skin was due to the action of photons.

Today, after the lapse of thousands of years, everything in nature has remained as before. Each morning the sun rises in the east; the water in the river freezes at zero degrees Centigrade, and red-hot metal cools according to the eternal laws of thermodynamics.

But now we do know about all these things. Perhaps our knowledge has not made us happier (for it is said: "In much wisdom is much grief; and he that increases knowledge increases sorrow"), but this knowledge is irreversible; it is an element of *culture* which

alone distinguishes us from the primitive shepherds, and whose boons and burdens it is almost impossible now to renounce. The whole complex of knowledge that we call culture has so radically changed the mode of life and the scale of values of civilized peoples that many are inclined to classify them as a different biological species rather than the one to which our ancestors, from whom we descended, belonged.

Now this huge amount of knowledge threatens to crush mankind, the same mankind that has called it into being. We frequently hear declarations that science has reached a deadlock, that it is developing more rapidly than it can be understood; that it has bogged down in details and lost its great ideals. And too many people repeat the effectual words of Thomas Stearns Eliot: "Where is the Life we have lost in living?/Where is the wisdom we have lost in knowledge?/Where is the knowledge we have lost in information?"

Such arguments always impress people who are weary or disillusioned. But despite this hopelessness, no matter how rarely it may be, a spark of talent will suddenly become a blaze, illuminating something very simple and important in the chaos of facts and opinions. Then everyone forgets his complaints and stops bickering over details. They tacitly share the delight over the new revelation. Like any manifestation of perfect beauty, it is rare, amazing and disarms one by its indemonstrable power.

I hope that everyone who has read this book to the end will share with me the joy and wonder that I once experienced when I first entered the unusual world of quantum mechanics.

NAME INDEX

TO THE READER

Mir Publishers welcome your comments on the content, translation and design of this book. We would also be pleased to receive any proposals you are to make about our future publications.

(Our address is:

USSR, 129820,
Moscow I-110, GSP
Pervy Rizhsky Pereulok, 2
MIR PUBLISHERS

Printed in the Union
of Soviet Socialist Republics

D. Leonid Ponomarev is a young theoretical physicist who has already done a great deal of research in the Laboratory of Theoretical Physics of the Joint Institute for Nuclear Research at Dubna (USSR). He has published numerous important papers on various problems of atomic physics and quantum mechanics. This work concerns mesic chemistry and the three-body problem in quantum mechanics. Recently, since the Russian edition of this book was published, he took his Doctor of Science degree in physics and mathematics at this institution.

One of D. Ponomarev's great hobbies is hiking and he spends much of his spare time and vacations on trips all over the Soviet Union. In the present book he has tried his hand for the first time to give the general reader an idea of how mankind gets to know the laws of nature, of what scientific work really consists in, about the history of one branch of physics and the men who had spent their lives advancing the science of the atom. He has tried here to narrate the founding and development of the ideas of quantum physics in a style which is lucidly clear and readable, yet completely sound scientifically.

D. Ponomarev's ultimate aim has been to have the reader share the joy and wonder accompanying the creative process in science and the eventual discovery of the essence of physical phenomena.